TÉCNICO LISBOA

Needs of Energy Storage to Supply the Urban Services in Peripheral Areas

Approach to Sustainability Cities

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Abstract

The energy transition towards the change of the current energy model into a new distributed model based on renewable energies is a growing public demand in a social environment. To ensure that cities and human settlements are inclusive and sustainable, it is necessary to bring shared self-consumption into their industrial states, where normally most city's energy is consumed. Nevertheless, current laws in most countries, such as Portugal or Spain, does not exploit shared self-consumption in full potential nor do they know the methodology to apply and carry out the energy transition model in cities.

This thesis will present an optimization problem of shared energy for applying in industrial states of cities based on the study of the electricity and water consumption pattern of enterprises and the use of shared self-consumption combined with a hybrid system (PATs and PV Solar), with the aim of reducing the total bill of every energy community during the year. This optimization is not only in the energy storage systems, but is important in water distribution networks as well. These pipes consume large amounts of water resources that need to be recovered energetically, using innovative solutions as small and micro-hydropower systems (particularly pump working as micro-turbine).

The final scenario and analysis showed interesting values related to environmental reductions of CO_2 emissions and economic indicators. Consequently, according to the criteria developed in this research project and the results obtained from the analysed models, the first step would be to use On-Grid systems for the industrial energy communities with the highest consumption and for those that generate less, Off-Grid systems.

Keywords: energy community, hydraulic energy, hybrid system, photovoltaic, self-consumption.

Resumo

A transição energética para a conversão do actual modelo energético num novo modelo distribuído baseado nas energias renováveis é uma procura pública crescente num ambiente social. Para assegurar que as cidades e as aglomerações humanas sejam inclusivas e sustentáveis, é necessário trazer o autoconsumo comum para os seus estados industriais, onde normalmente é consumida a maior parte da energia da cidade. No entanto, as leis atuais na maioria dos países, como Portugal ou Espanha, não exploram o autoconsumo compartilhado em pleno potencial, nem conhecem a metodologia a ser aplicada para executar o modelo de transição energética nas cidades.

Esta tese apresentará um problema de optimização da energia partilhada para aplicação em estados industriais das cidades com base no estudo do padrão de consumo de electricidade e água das empresas e da utilização do autoconsumo partilhado combinado com um sistema híbrido (PATs e PV Solar), com o objectivo de reduzir a factura total de cada comunidade energética durante o ano. Esta optimização não se verifica apenas nos sistemas de armazenamento de energia, mas também é importante nas redes de distribuição de água. Estas condutas consomem grandes quantidades de recursos hídricos que necessitam de ser recuperados energeticamente, utilizando soluções inovadoras como sistemas pequenos e micro-hídricos (particularmente bombas que funcionam como micro-turbinas).

O cenário e a análise final mostraram valores interessantes relacionados com as reduções ambientais das emissões de CO2 e com os indicadores económicos. Consequentemente, de acordo com os critérios desenvolvidos neste projecto de investigação e os resultados obtidos com os modelos analisados, o primeiro passo seria a utilização de sistemas On-Grid para as comunidades energéticas industriais com maior consumo e para as que geram menos, sistemas Off-Grid.

Palavras-chave: autoconsumo, , comunidade energética, energia hidráulica, fotovoltaica, sistema híbrido.

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List of Acronyms

C / P	Pipe
CEC	Citizen Energy Community
DNO	Distribuiton Network Operation
EC	Energy Community
H	Hydrant
HDKR	The Hay and Davies, Klucher and Reindl model
IDAE	Institute for Energy Diversification and Saving
IEC	Technical standards
J	Node or Junction
PAT	Pump-as-Turbine.
PMP	Pump
PV	Photovoltaic
RD	Royal ordinance
REC	Renewable Energy Community
SA	Limited Liability Company (Spanish company designation)
SABI	Iberian Balance Sheet Analysis System
SL	Limited Company (Spanish company designation)
SMC	Meteorological Service of Catalonia
SME	Small to Mid-size Enterprise
T	Tank
TB	Turbine

List of Symbols

A_i	Relation between beam diffuse component and extraterrestrial normal irradiance
AIC	Akaike Information Center
A_{oc}	Occupancy of the panels
B	Battery capacity
b	Battery charge at time t
b_e	Electricity from battery to surplus at time t
b_k	Electricity from battery to consumer k at time t
C_D	Cost of electricity demand at time t
C_E	Cost of electricity surplus at time t
C_d	Maximum daily discharge of battery
C_e	Maximum seasonal discharge of battery
c_{ins}	Initial investment or total costs
c_{TB}	Total turbine costs
$c1$	Sale of surplus energy to the electric company
$c2$	Net benefit of the energy generated from renewables that will no longer be paid to the supplier
D	Consumption of consumer k at time t
DLS	Day Light Saving coefficient
D_{k_n}	Water demand of each company (n)
D_{k_T}	Total water demand of the companies
d	Maintenance gap between PV panels
d	Demand of consumer k at time t
d_{12}	Distance between two companies

ENG_h	Total net hourly energy produced by the installation
EC_n	Total electricity consumption per company (n)
e	Global system surplus at time t
F_c	Snedcor F test
F_{tab}	Coefficient obtained from the F distribution table with k degrees of freedom in the numerator, $n-(k+1)$ in the denominator and taking into account a significance level
$F_{\tau,b}$	Dirtiness index of beam component
$F_{\tau,d}$	Dirtiness index of diffuse component
$F_{\tau,g}$	Dirtiness index of ground component
f_{atm}	Atmospheric correction
G	Total generation at time t
G_b	Beam component of irradiance
G_d	Diffuse component of irradiance
G_g	Ground component of irradiance
G_{on} , G_o	Extraterrestrial normal irradiance
G_T	Total irradiance
$G_{t\,eff}$	Effective total irradiance
$G_{[pyro\,802]}$	Irradiance Horizontal surface (calculated by radiation pyrometer)
Gsc	Solar Irradiation
g	Gravity
$g_{PV,b}$	PV and Turbine generation to battery at time t
$g_{TB,b}$	PV and Turbine generation to battery at time t
$g_{PV,e}$	PV and Turbine generation to surplus at time t
$g_{TB,e}$	PV and Turbine generation to surplus at time t
$g_{PV,k}$	PV and Turbine generation to consumer k at time t

$g_{TB,k}$	PV and Turbine generation to consumer k at time t
g_{CO2}	Total reduction of CO_2 emissions
g_{ins}	Benefits of the installation
H	Waterfall from the main tank
He	Operation hours
HSP	Peak Solar Hour
H_0	Correct model
H_1	If H_0 is false
h	Distance between top point of the PV panel to the roof
I_T	Total irradiation
$I_{t\,eff}$	Effective total irradiation
i	Initial estimated values prior to any iteration
j	Initial estimated values prior to any iteration
k	Consumer index
k	K-factor according to the zone
k_t	Clearness index
K	Number of consumers
L	Length of the PV panel
L_{md}	Average of daily consumption
L_{st}	Longitude of the zone
N	Day of the Year
N_p	Number of PV panels in parallel
N_{PV}	Number of PV Panels installed
N_s	Number of PV panels in series
N_a	Number of days of autonomy desired in the battery

$\boldsymbol{P_{ELECT}}$	Electric power
$\boldsymbol{P_{k\_n}}$	Per capita electricity cost for each company (n)
$\boldsymbol{P_H}$	Hydraulic power
$\boldsymbol{P_{PV}}$	Power of PV panel
$\boldsymbol{p}$	Probability of obtaining a value equal or higher than the observed value, assuming that the null hypothesis is true
$\boldsymbol{p_{k\_T}}$	Pressure of the general pipe of the energy community
$\boldsymbol{Q_{k\_T}}$	Flow of the general pipe of the energy community
$\boldsymbol{R^2}$	Determination coefficient
$\boldsymbol{R_b}$	Relation between the cosines of the beam's inclination and the zenith angle
$\boldsymbol{SIC}$	Schwarz Information Center
$\boldsymbol{S_n}$	The solar capacity (rooftop area capable to install PV panels) of each company (n)
$\boldsymbol{SQR}$	Sum of the squares of the waste
T	Number of periods
t	Time index
$\boldsymbol{t_{(n-k-1)}}$	t – Student coefficient
$\boldsymbol{t_{solar}}$	Solar time
$\boldsymbol{t_{clock}}$	Clock time
$\boldsymbol{u_{it}}$	Error term
$\boldsymbol{W_n}$	Total number of workers in the company (n)
$\boldsymbol{w}$	Width of the PV panel
$\boldsymbol{x_{jit}}$	Explanatory variables, such as j = 1, …, k
$\boldsymbol{V}$	Volume of tank
$\boldsymbol{V_b}$	Battery voltaje difference
α	Significance level

β	Inclination of panels
β_0	Separate term
β_j	Unknown regression coefficients, such as j = 1, …, k
ϒ	Azimuth of panel superficies
ϒs	Solar azimuth
Δ	Variation/Deviation.
δ	Declination angle
η	Battery efficiency
η_{em}	Electro-mechanic efficiency
η_{PV}	Efficiency of PV panel
η_{turb}	Efficiency of installed turbine
θ_z	Zenith angle
θ	Angle between the sun beams and the surface of the panel
μ	Battery depth of discharge
μ_d	Maximum daily discharge coefficient
μ_e	Maximum seasonal discharge coefficient
ρ	Water density
ρ_g	Ground view factor
σ^2	The standard deviation
φ_i	Coefficient of distribution of the energy generated for the consumer "i".
Φ	Latitude of the zone
∅	Diameter of tank
ω	Angle of the sun in relation to its position at noon

Chapter 1

1 Introduction

1.1 Main Approach

The world's population is constantly increasing. To accommodate everyone, we need to build modern and sustainable cities [2] (**Global Goals, 2020**). Since the last decade, many researchers have looked at new and alternative ways to generate and distribute energy. Many developed countries have been applying new methodologies to create energy communities using their own resources such as solar, wind or water for several years now. Specifically, in Europe, different concepts have been defined of what an energy community means [14] (**Roberts, 2019**), and in all these definitions similar words appear as shareholders, voluntary participation, environment and economic, financial or social benefits.

Mainly, there are two valid definitions in European legislation, the first one from the Renewable directive, REC, Renewable Energy Community and the other one from the Electricity directive, CEC, Citizen Energy Community. The differences between the CEC and REC definitions also help to explain the overall relationship between them: namely, that RECs can generally be seen as a subset, or type, of CEC. This helps rationalise the narrower geographical scope of activities of RECs compared to CECs. In technical terms, the main difference is that RECs are defined to always operate autonomously, whereas CECs could act as RECs or be connected to the distribution network of the marketer.

The main problem lies in the inconsistency or ambiguity in the European framework of the application of these definitions in local areas such as industrial estates. Today, most industrial areas in developed countries do not have an energy improvement plan and lack government support for their transformation. For this reason, in this thesis, a model or pattern will be designed for the search of potential companies and industries, capable of entering to the project of energy communities' creation and industrial states transformation, towards the energy transition. What is attempted is to explain a development model to follow in order to face an energy transformation in any industrial area with sufficient resources to apply it. It is obvious that each case is completely different at the level of the final solution but it has been tried to show the way or the necessary guidelines to follow.

In any type of energy community there will be associated producers and consumers, who will be the agents to start working together. An owner of the installation must also be part of it, who will be the one who registers as the owner of the generating installation normally for self-consumption. In many cases, this may be the same consumer and may be shared between several consumers at the same time. There are many ways of self-consumption, depending on the regulations of each country. In this thesis, methodologies for self-consumption connected to the grid with surplus sale (CEC) and autonomous installations disconnected from the general electricity grid (REC) will be evaluated.

The model will be implemented locally in one industrial estate of a Spain's city as a particular case of the project. The city in question is Granollers, an industrial city located in the province of Barcelona, in the region of Catalonia. This city has been chosen for its high electricity consumption in its industrial area, approximately 55% in relation to the whole city, and for its large number of companies (mostly SMEs) that generate 4 billion euros in turnover per year. Moreover, this case has been taken advantage of because an investment or scholarship is available to develop an innovative project in the city.

Although it has 7 industrial estates in total, the study will only be carried out in the two adjacent ones which are located in the highest area of the municipality (approximately 170 m) and which, by chance, are awaiting a complete renovation in terms of municipal equipment. In this way, a previous study will be developed for the use of a hybrid methodology with renewable energies sufficiently coherent with the resources available in the area. Currently in Spain, the development of renewable energies is far below its possibilities due to the capitalization of the electrical companies and the lack of promotion of change by the state authorities. Since 2019, regulations have been improved for the implementation of solutions with photovoltaic panels that reduce the periods of return (Paybacks) on investment. In this thesis, this methodology is used together with micro-turbines (PATs) taking advantage of the hydraulic resources consumed by companies in industrial areas and thus improve environmental levels.

The main idea is to design an optimization model and calculate the best options (both economic-financial and environmental) for each particular case of energy community. This model will be subsequent to the statistical study of all the companies on the industrial estate for the evaluation of the potential users for becoming part of an energy community.

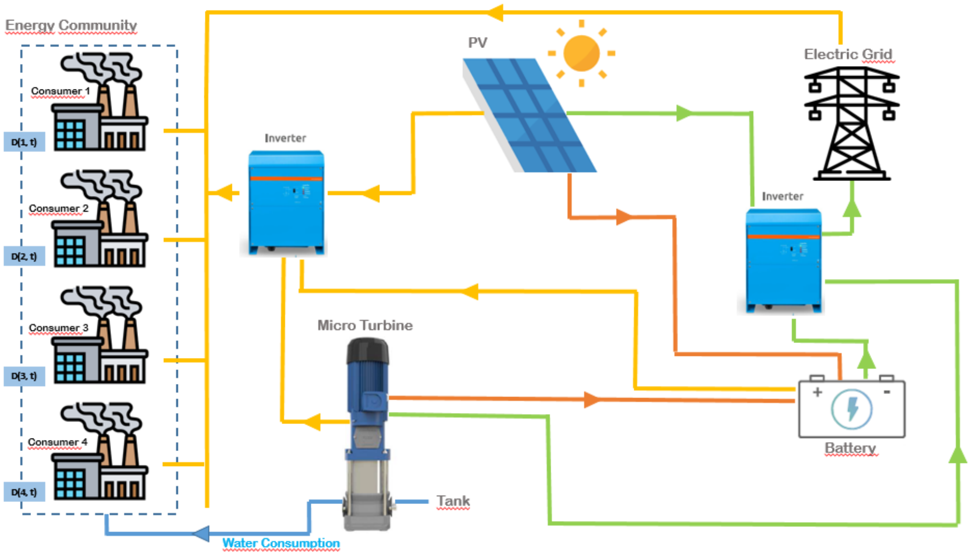


Figure 1.1: *Optimization model to analyse.*

1.2 Objectives

The aim of the master thesis is to develop a strategy to establish the energy improvement plan in the peripheral area (especially at industrial states), as well as enhancing their energy systems, through a renewable system that should contain solar radiation and water resources (including hydraulic micro-turbines). Pump as turbine (PAT) is a form of energy recovery normally equipped in the water-pressurized networks. PATs can be used in any pipe system with excess of flow energy being more suitable for water supply networks, irrigation systems, industry processes, drainage or storm systems and treatment plants or at the entrance of reservoirs/tanks. The range operation (i.e., flow and head) is high and depends on the selected machine. Commonly, the flow rate is between 1 and 100 l/s and the head rate oscillates between 1 and 80 m w.c. (meters water column). Sub-section 6.1.1 *Hydraulic Energy System* will describe a deep analysis of the use of PATs in pipe systems and their operation rate.

The proposed strategy includes an optimization of the system that will contain uncertainty in the resources and it should be applied in a real case study. From the most desirable situation defined previously, the following steps are established to achieve the main objective:

(i) Analyse the state of the art in the topic "sustainable cities using renewable resources". To this end, it is necessary to adapt it to the peripheral areas and to establish a study pattern for the industrial estates and to evaluate all member companies according to variables such as the number of workers, turnover, water and electricity consumption, among many others. Following this, define the participation of all companies or potential clients in each viable project.

(ii) Establish groups of companies capable of sharing energy (with Smart Grid or not) and have an autonomous system (if feasible) for each group from the hybrid solution adopted with renewable energies. For the establishment of these groups, it will be necessary previously to review and evaluate national, regional and local legislation and/or technical limits related to the creation of energy communities. Especially at the level of the commercialization of the electrical energy in the area. In addition, it will be necessary to create a model to calculate the electricity and water consumed by the companies in the area, according to some type of variables such as the surface of the industrial warehouse, number of workers, turnover and type of industry. A previous study or energy audit of some companies in the industrial area will be necessary for the real validation of the data obtained for the model.

(iii) Identify the renewable energy resources (Solar, Wind, and Hydraulic) that exist in the work area and assess the solar capacity, studying the structural boundaries of the available rooftops of companies and municipal equipment areas. Also developing a study of the municipal water network using WaterGems software and obtain the pressures due to the water heads and therefore the energy that we will have in each area of the industrial state, directly related to water consumption of companies.

(iv) Design a hybrid autonomous system using renewable energy, if possible, with photovoltaic panels and hydraulic micro-turbines. These systems provide two benefits: on the one hand, PATS contributes to the improvement of the global energy balance and increase the efficiency in the water network of the industrial estates; on the other hand, PV panels provide the most energy to the system and complement a cost-effective solution for SMEs and businesses.

(v) Create an optimization model of the hybrid autonomous system and evaluate the environmental and economic impact of the solution provided. This MATLAB model would have to be generic and completely extrapolated to different cases of energy communities in order to adapt the chosen renewable and/or hybrid solutions, in a quick and efficient way.

Chapter 2

2 Background

Today, not all but many cases in industry have a very distant and basic attitude towards energy: it is only consumer. It is true that efforts have been made to reduce consumption by improving energy efficiency, but in general, this is not enough, so the promotion of energy sharing is now a necessary step.

According to a 2018 study by ICAEN[1] and Table 2.1, Catalan industry consumes 27.3% of the total energy consumed in Spain (natural gas and electricity), which is produced mainly by thermoelectric and nuclear generation. Although Catalonia consumes 17% of the electricity in Spain, more is consumed than is generated, 17.1% of energy generated versus 17.8% consumed.

Year 2017 GWh	Catalonia	%	Total Spain
Hydraulic	3.720	20.3	18.364
Turbine / Pumping	114	5.1	2.249
Nuclear	24.233	43.6	55.609
Coal	0	0	45.196
Fuel / gas	0	0	7.011
Combined cycle	7.893	21.2	37.296
Hydropower	0	0	20
Eolic	2.825	5.9	47.897
Photovoltaic solar	420	5	8.385
Thermal solar	87	1.6	5.348
Other renewables	191	5.3	3.614
Cogeneration	5.082	18	28.170
Non-renew. waste burning	145	5.6	2.608
Biogas	141	16.1	877
Total net generation	**44.852**	**17.1**	**262.645**
Pumping consumption	-165	4.5	-3.675
Total Demand	**47.652**	**17.8**	**268.140**
Δ% 2017 / 2016	**2,4**	**-**	**1,2**

Table 2.1: *Electricity balance of Catalonia and Total of Spain.*

Distributed generation from renewable energies places citizens and especially the peripheral areas of cities, where most of the energy is consumed (between approximately 30% and 60% of the city), at the centre of the new energy model. These areas are a good place to start investigating because they are clustered into large energy consumers and potential producers such as Fig. 2.1.

[1] Catalan Energy Institute: body that promotes energy policies in the region of Catalonia.

Figure 2.1: *Distributed energy model.*

The majority of companies on industrial estates are not sufficiently motivated or prepared to implement major changes in energy issues due to their small size and internal day-to-day problems. They do not know exactly what an energy transition is about, partly because they do not have enough information, background and time to devote to it.

In general, there are gaps in basic infrastructure and adequate telecommunications services are not always available to deal with the energy transition. The implementation of actions designed to solve these problems are the basis that will unify the starting point and will help to identify those areas of economic activity that are best positioned to initiate a process of energy transition. Furthermore, companies must have an active and effective associative structure with a good relationship, where the critical point is not the technological but the social one.

2.1 Main issues

The main challenges arising from the promotion of the energy transition in industrial estates and peripheral areas of cities for their sustainability are very complex. It is as much of an economic, structural, and distributive nature as it is in the process of installation itself. The main aspects or issues are:

(i) **Asset control of energy community**: the energy community (EC) needs a responsible operator able to take operating decisions. This user have to control the production, storage and networks of the micro grid. There is considerable regulatory uncertainty as to how and when the role of Distribution Network Operator (DNO) will evolve to incorporate more system operation responsibilities.

(ii) **Participation in grid system operation**: the benefit from creating ECs with controllable loads, generation and storage is that they enable a higher penetration of distributed renewables in the electricity system. However, it is not clear that there is a process by which energy communities can be remunerated for the provision of grid services under the current market and regulatory arrangements.

(iii) **Obligations of connections**: the obligations placed on network of the energy communities are especially demanding and stem from the natural monopoly characteristics of these assets. Normally, these obligations are justified by the need to prevent the inefficiency of the duplication of network. In conclusion, there are many aspects around the distribution network operator and a local network that would challenge the existing regulatory framework.

(iv) **Administrative burden**: almost all of the licencing requirements will impose an administrative cost on Energy communities.

(v) **Regulated benefits**: is necessary to protect customers from mismanagement of great providers and adopt procedures designed to incentive end-users to use of renewable energies and specifically in the energy compensation.

(vi) **Settlements arrangements**: to implement direct trading between end-users, they have to take over settlement responsibility for their own meters. Now, the current arrangements do not support directly this idea and provide the control of it by a single responsible. The process for coordinating the procurement of network services across the transmission and distribution levels is ambiguous.

(vii) **Free choice of supplier**: normally some suppliers pose different problems when you want to create an energy community, putting it in a prolonged blockage period if you do not buy electricity from them.

(viii) **Connecting hybrid models in smart grids**: it is not defined in regulatory requirements how to implement a hybrid solution associated to energy communities. Hydraulic turbines or pumps are not usually used in energy communities because is difficult to share and deliver this energy between consumers.

2.2 Previous Project Information

2.2.1 Location and Environment

The study will be focused on the city of Granollers, located in the province of Barcelona, within the region of Catalonia and eastern Spain. This city has seven industrial estates with a useful surface of 273 hectares and more than 650 business activities where approximately 4000 million euros of turnover is generated per year. These companies provide employment for 12,000 workers in the area, being the second city in Catalonia with the highest percentage of employment in the sector.

The energy consumption of the companies corresponds to 47% of the total of the city, with a consumption in natural gas of 44% and a 55% in electricity. Below, Fig. 2.2 shows energy consumption by sector in the city:

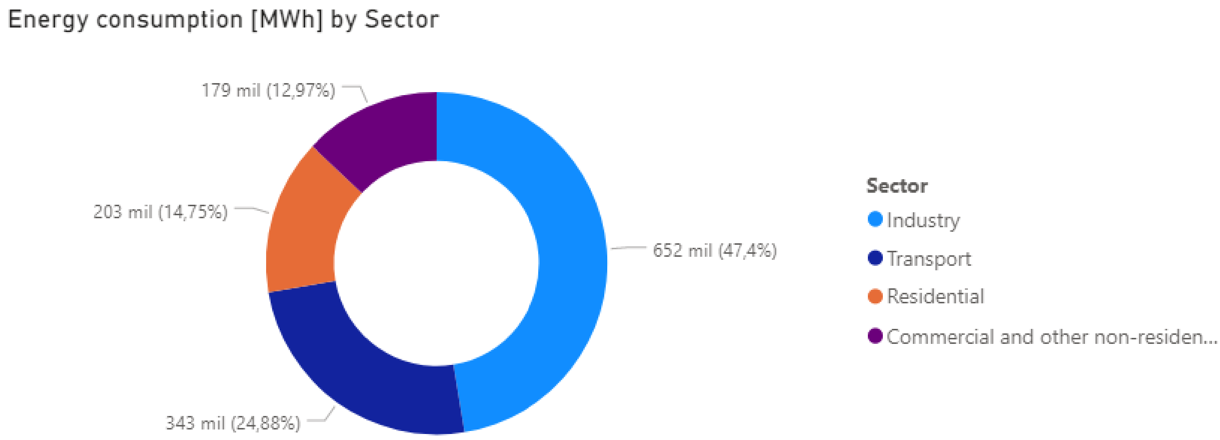


Figure 2.2: *Energy consumption by sectors in Granollers (2012).*

In this thesis, the impulse towards the energy transition will be evaluated for the specific cases of the two industrial areas of the city with the highest altitude: Coll de la Manya [17] and Font del Ràdium [18]. The main objective is to implement energy solutions through renewable energies (hydraulic and photovoltaic) in order to improve the circular economy among the companies of these industrial areas and to give a solution that permits to reduce the electrical consumption and the CO_2 emissions to the atmosphere. Companies from all sectors are located in these estates, such as Logistics, Food, Automotive and Pharmaceuticals. It is worth noting the location of multinational and international companies with factories for the production of their important products, such as Mondelēz International, Pierre Fabre or Karcher.

Figure 2.3: *Location of industrial states studied.*

These two industrial estates, shown in the Fig. 2.3, are made up of 134 companies, developed in 2005 and 1991, respectively, and cover an area of 93.86 hectares. Employment capacity is 2571 workers and they have an annual turnover of 682 million euros.

2.2.2 Prior Regulatory Requirements

Before undertaking some solution, it is necessary to carry out a research of the main regulatory requirements of the area in terms of self-consumption and energy communities.

As a result, Real Decreto 244/2019[2], 5th April, establishes that *"a consumer participates in collective self-consumption when he or she belongs to a group of several consumers who are supplied, in an agreed manner, with electrical energy from production facilities close to those of consumption and associated with them".* In other words, a collective self-consumption will be formed by one or more electrical energy generating installations and several consumers that are associated with them.

The connection of the collective self-consumption installations may be carried out in an internal electric network, by using direct lines, or across a network, if in the latter case one of the following requirements are fulfilled:

(i) The connection is made to the LV network which is derived from the same transformer station to which the consumer belongs.

(ii) Both generation and consumption are connected in LV and at a distance between them of less than 500 m, measured in orthogonal projection on the floor between the measuring equipment.

(iii) That the generating installation and associated consumers are located in the same cadastral reference, taken as such if the first 14 digits coincide (with the exception of Autonomous Communities with their own land register regulations).

The collective self-consumption may also belong to one of the modalities of self-consumption contemplated by RD 244/2019 in Article 4, so that they may exist:

a) <u>Collective self-consumption WITHOUT surpluses</u>**:** Composed of several associated consumers and will have an anti-spill system that prevents the transfer of energy to the network. In this case, all associated consumers shall share the ownership of the generation facility and the anti-spill mechanism jointly. The advantage of compensating for individualised surpluses is not taken advantage of, hence the following option being more recommendable.

b) <u>Collective self-consumption WITHOUT or WITH surplus under compensation</u>: Collective facilities without surpluses subject to compensation are an exclusive particular case of collective self-consumption. The installation shall be equipped with an anti-spill system so that energy can never be transferred to the network. However, consumers can benefit from the surplus compensation mechanism. All associated consumers will also share the ownership of the generation installation and the anti-spill mechanism jointly.

c) <u>Collective self-consumption WITH surpluses not subject to compensation</u>: In this case, the ownership of the generation facility belongs to the producer. Various consumers will be involved and the non-self-consumed surpluses will be sold to the market. Those surpluses, which will be

[2] Real Decreto 244/2019: Spanish regulations establishing the administrative, technical and economic conditions for the self-consumption of electrical energy.

associated to the generation facility (or facilities), are calculated as the difference between net hourly generation and the sum of individualized hourly self-consumption.

In a collective self-consumption all the associated consumers must belong to **the same mode** of self-consumption. It is necessary for the participants to sign an **agreement with the criteria for the distribution of the energy generated**. This agreement must be signed by all the associated consumers and sent individually by each of them to the distribution company (directly or through its marketer).

This distribution of energy may be carried out with the best possible criteria to satisfy the needs of the consumers, with the only constraint of using fixed distribution coefficients, and the sum of these coefficients must be one[3].

In all cases, for each consumer associated with the self-consumption facility, the "individualized net hourly energy" shall be calculated as:

$$ENG_{h,i} = \varphi_i \cdot ENG_h \tag{2.1}$$

Where:

ENG_h= total net hourly energy produced by the installation.

φ_i = coefficient of distribution of the energy generated for the consumer "i".

This coefficient must be included in the consumer sharing agreement and must fulfil the following limitations:

(i) It must be constant distribution for each consumer at all times during the billing period (month).

(ii) The sum of the φ_i of all consumers associated with the same self-consumption facility must be 1.

(iii) φ will take the value 1 when there is only one associated consumer.

In the calculation of φ_i, whichever criteria are agreed between the associated consumers can be used. However, Annex II of RD 244/2019 proposes a formula for calculating the coefficients based on the contracted power of each of the consumers.

$$\varphi_i = \frac{Maximum\ power\ contracted\ (consumer\ i)}{\sum Maximum\ power\ contracted\ (all\ consumers)} \tag{2.2}$$

[3] Final provision 5 of RD 244/2019 empowers the Minister for Ecological Transition to modify these restrictions by enabling the existence of dynamic coefficients under certain conditions.

Chapter 3

3 General Data and Features of Area

3.1 Renewables Sources in the Area

Located in the hills west of the city, the area is not characterized by rivers or tributaries with large water flows, in order to install hydroelectric plants or solutions with large turbines or hydraulic pumps.

The wind currents to install Eolic turbines are not a recommendable solution either, and it is that according to the data provided by the nearest SMC[4] weather station, the average wind speed at 10 meters high is 1.81 m/s, with a maximum daily gust of 8.27 m/s. These results are attached in the annex of the project, which are extracted for the years 2018-2019 and it can be verified in Fig. 4.1 obtained from the European Meteorological Society (EMS). It is not necessary to mention, the visual impact that could cause wind turbines of these dimensions located in the highest part of the city.

In the same annex, there are also data on solar radiation in the area, where in comparison to other European countries, a good measure is obtained for obtaining this type of energy through photovoltaic panels. According to the map obtained of this area, as it is shown in Fig. 3.1 and 3.2, between 1300 and 2100 kWh / m^2 of global horizontal irradiation (GHI) is obtained for the whole year.

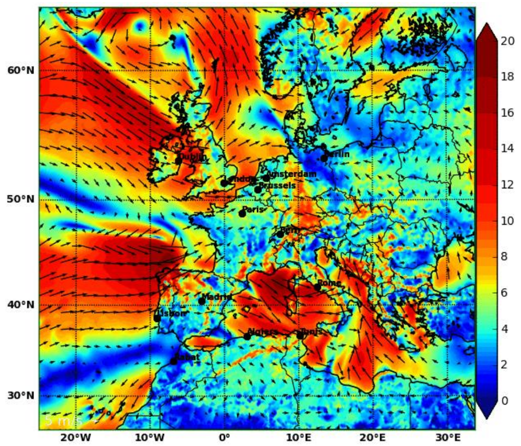


Figure 3.1: *Wind speed of Europe from source Meteonorm 7.1.*

[4] Meteorological institute of the Catalonia's region, Spain. Provides information about weather and meteorological phenomena.

Yearly sum of Global Horizontal Irradiation (GHI)

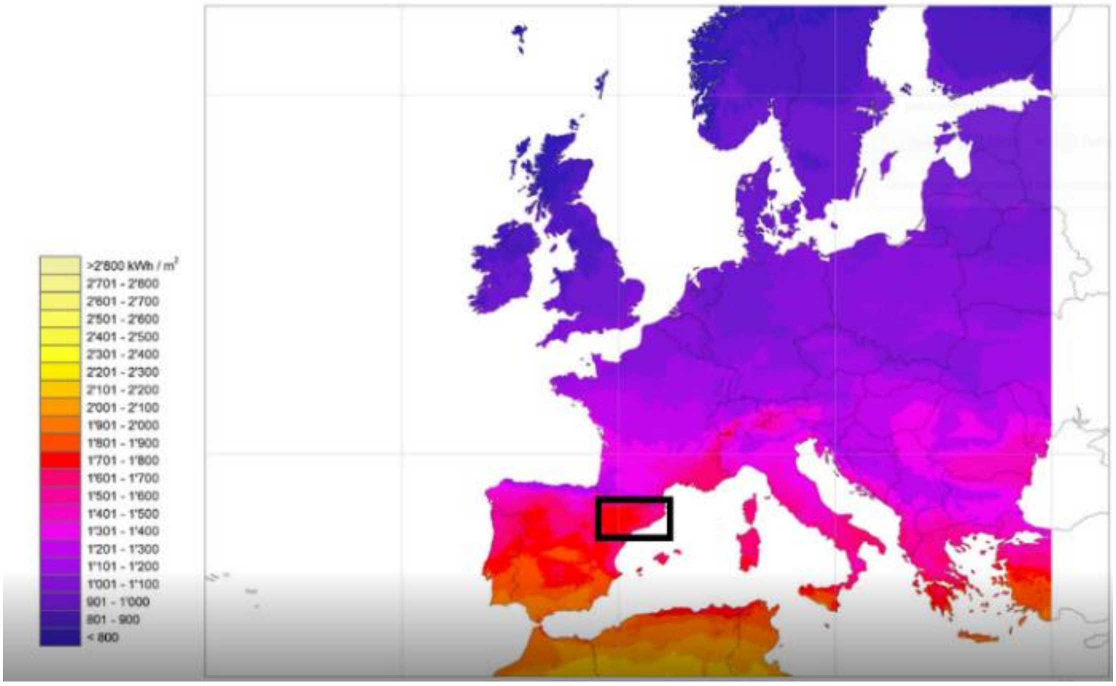


Figure 3.2: *Yearly sum of Global Horizontal Irradiation of Europe from source Meteonorm 7.1.*

Due to the lack of hydraulic resources in the area, such as rivers or reservoirs, the possibility of developing a solution to exploit the water consumption of the different companies in the industrial areas through the water distribution network will be studied. This is a totally sustainable solution with the environment because it takes advantage of resources that will be consumed at all costs by the workers in the industry of Granollers. If this energy is not recovered, than it is wasted.

Finally, it has been ruled out to evaluate energy sources such as geothermal or marine hydraulics because of the lack of seismic movement in the area and the absence of strong water currents due to it is not a coastal area.

3.2 Obtaining Real Data

For the analysis of the area, the databases of the Industrial Estate Associations registered in the city where the particular case is located have been used. In them, basic data can be found such as the NIF, location, name of the company and contact email.

The remaining information is based on databases posted on the Internet, such as SABI's[5] database on economic issues (invoicing, number of workers, expenses, etc.) and tools used by some institutions such as the IDAE[6] for energy topics.

[5] "Iberian Balance Sheet Analysis Systems" - a tool that contains information on the balance sheets presented by more than 1.2 million Spanish companies and 400,000 Portuguese companies

[6] Institute for Energy Savings and Promotion.

After validation and treatment of the collected information, only those companies that fulfilled the necessary requirements in the study of potential customers in order to be integrated in the shared energy management project (Chapter Shared Projects) were considered for the study. This approach made it possible to work with balanced data for the years 2018 and 2019. The cases that have not been considered for this are referred to as "inconclusive companies", which had incomplete information, especially in terms of consumption.

As part of this research, a sample for electricity and water consumption was obtained from 50 companies located in the Coll de la Manya and Font del Ràdium industrial estates in the city of Granollers. The format includes the following categories or types of companies in the Food, Pharmaceutical, Logistics, Automotive, Metallurgical and Solar sectors, among many others.

In this way, relevant information such as the annual electricity consumption has been requested through a form sent to companies and checked through a data download kit for electricity meters. This device, shown in Fig. 3.3, is used to download the historical data of the last 6 months from the company's meter and only for those who comply with the **IEC 870-5-102[7].**

The electricity consumption data are indirectly added in Table C.1, through the electricity expenses column, because the companies have not given the confidentiality to show them. These data have been provided in an aggregated format for the last year of consumption, i.e. 2019.

Figure 3.3: *Kit IEC to download data from electric meter to mobile.*

In addition, the local water company has been requested to provide the annual water consumption of these companies during the year 2018 and 2019.

[7] Spanish standard for measurement equipment in energy facilities.

3.3 Consumption Definition

3.3.1 Treatment of variables

In order to create a pattern for assessing companies on industrial estates, it is necessary to deal with the variables for which yearly information has been collected from 50 enterprises. These are the surface area of the industrial building, the company's turnover, the number of workers, the hours worked during a year by all workers, the annual water consumption, the annual thermal consumption, the money spent on salaries annually and the following ratios. Important ratios to evaluate the per capita water consumption and cost. The electricity consumption has not been evaluated because it is data validated with the measurement kit and it is not necessary to evaluate the correlation between the other variables. Furthermore, it will be used as an independent variable in the regression model explained below.

$$R1 = \frac{number\ of\ workers}{water\ consumption} \qquad R2 = \frac{number\ of\ workers}{water\ bill}$$

The nomenclature of the variables is as follows:

M_2 Surface area of the industrial building.

turn Company's turnover or billing.

n_work Number of workers of the company.

hor_work Hours worked during a year by all workers.

Cons_H2O Annual water consumption of the company.

Cons_Term Annual thermal consumption where uses the heat for a wide variety of applications, including washing, cooking, sterilizing, drying, preheating of boiler feed water, process heating, and much more.

Firstly, it is necessary to carry out a correlation study of these variables to rule out those that are considered statistically equal.

	M_2	turn	n_work	hor_work	Cons_H2O	Cons_Term
turn	0,561					
n_work	0,573	0,782				
hor_work	0,573	0,782	1,000			
Cons_H2O	0,615	0,568	0,575	0,575		
Cons_Term	0,246	0,177	0,185	0,185	-0,057	
Salaries	0,525	0,814	0,865	0,865	0,633	0,133

Table 3.1: *Analysis of the variables' correlations.*

It is observed in Table 3.1, that the variables number of workers (**n_work**) and hours worked by workers during a year (**hour_work**) are highly correlated because the correlation value is 1, so one will be discarded. Also in Figure 3.4, shows graphically all the correlation studies between the variables and it is observed how the regression line is completely linear for these two variables.

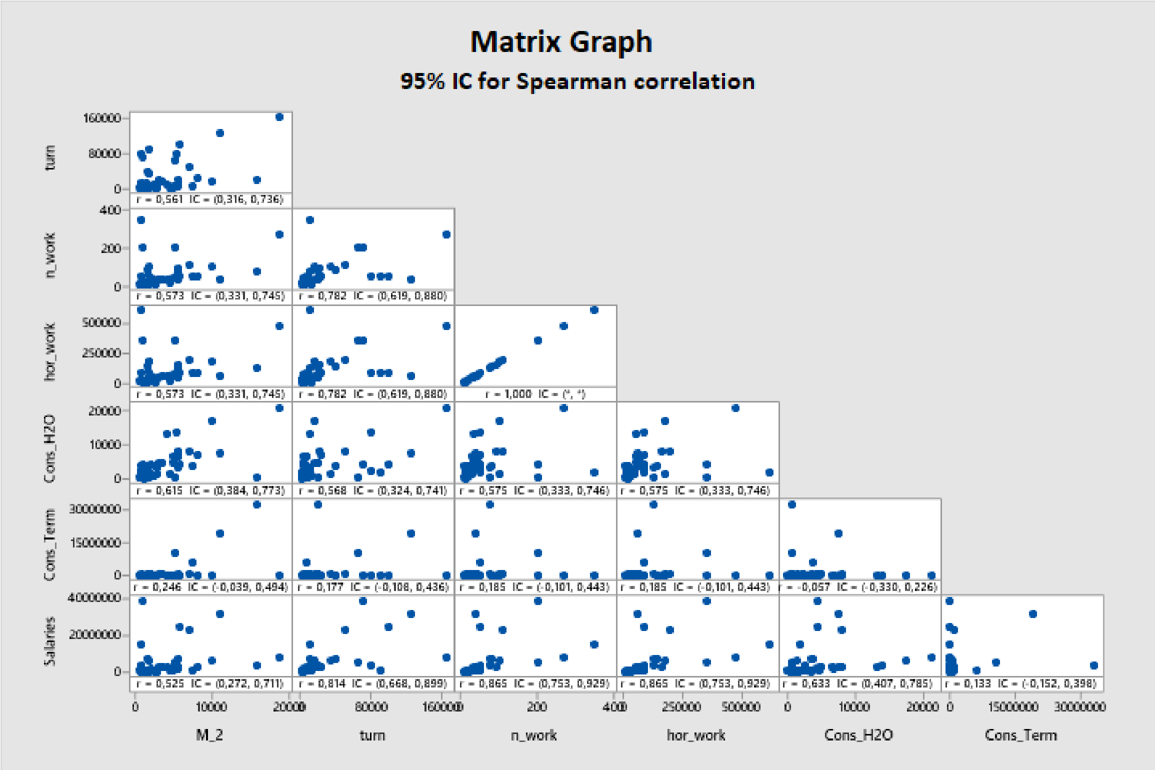


Figure 3.4: Comparison of variables' correlation.

Subsequently, with the resulting variables, a PCA (Principal Component Analysis) analysis was performed using Minitab software to reduce the number of variables to make the data easier to analyse.

From the results obtained in the Table 3.2, sufficient components are chosen to explain 95% of the variation in the data. The first main component represents 37.6% of the total variance. The variables that correlate most with this component are turnover (0.469), number of workers (0.426), salaries (0.392), water consumption (0.362) and thermal consumption (0.264). It is positively correlated with these five variables, therefore, by increasing its values, the value of the first main component (PC1) increases. The first five main components explain 95.2% of the variation in the data, so it was decided to use them to analyse the electricity models of the companies.

Own Value	3,0067	2,2380	1,1170	0,8357	0,4213	0,2901	0,0898	0,0014
Proportion	0,376	0,280	0,140	0,104	0,053	0,036	0,011	0,000
Accumulated	0,376	0,656	0,795	0,900	0,952	0,989	1,000	1,000
Variable	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**	**PC8**
M_2	0,456	0,141	-0,427	-0,312	-0,068	-0,071	-0,695	-0,026
turn	0,469	0,128	0,145	0,163	0,613	0,581	0,051	0,008
n_work	0,426	-0,122	0,382	-0,055	-0,720	0,357	0,076	0,055
Cons_H2O	0,362	0,343	0,122	-0,545	0,113	-0,410	0,508	-0,010
Cons_Term	0,264	-0,171	-0,750	0,278	-0,153	0,053	0,483	0,042
Salaries	0,392	0,047	0,249	0,662	0,008	-0,572	-0,125	-0,023
n_work/H2O Bill	0,141	-0,634	0,070	-0,164	0,143	-0,088	0,017	-0,719
N_work/H2O Consump	0,128	-0,630	0,080	-0,183	0,208	-0,158	-0,041	0,690

Table 3.2: *Analysis of the values and vectors of the correlation matrix.*

3.3.2 Linear Regression

Theoretical model

Two completely separate study models will be applied between "Electricity Consumption" and "Water Consumption". The model used for the industrial area is defined as follows:

$$C = h(x, t) + \varepsilon \tag{3.1}$$

Where,

C - Consumption function (Electricity and Water consumption)
h - Econometric simple linear regression ($Y_{it} = \beta_0 + \beta_1 x_{1it} + \cdots$)
x - Size Factors (m2, turn, n_work, hor_work, Cons_Term)
t - Periods
ε - Error term

Variable	Description
Cons_El	kWh of electricity consumed annually per industrial building
Cons_H2O	m^3 of water consumed annually per industrial building

Variable	Description
m2	Area of the industrial building [m^2] –> V. Quantitative
turn	Turnover in thousands of euros (10^3 €) –> V. Quantitative
n_work	Average number of workers per industrial building –> V. Quantitative
hor_work	Number of hours worked annually by workers –> V. Quantitative
Cons_Term	Thermal consumption in the industrial premises is according to CNAE. With value 1 if they have --> V. Binary

Table 3.3: *Dependent and explanatory variables of the model.*

The variables **m2**, **turn**, **n_work** and **hor_work** are designated as size factors because they characterize in a certain way, as the name suggests, the size of the industrial building or factory.

These variables are provided by a statistical study based on a first proposal related to the study of this topic by several authors. In their analyses, it is concluded that the total area of the establishments [1] (**Dwiegielewski, 2000**), the turnover of the company [4] (**Worthington, 2010**), the average number of hours worked per day per worker and the number of workers [3] (**Hobby, 2011**), are the major factors in the consumption of water and electricity. Hence, variables analysed in the previous sub-section 3.3.1, such as **Salaries**, the total sum of workers' salaries, are exempted from the linear regression due to a similarity of 62.8% with the **turn** variable. This statement has been obtained from the inherent values marked in green in Table 3.2. The methodology applied with its different steps and the theoretical results analysis of each model is developed in Appendix D.1 and D.2, due to the length of the method.

Electricity consumption model

The following tables present the models developed, and they show all the results including the coefficients of the regression (β_k), the standard error of the coefficients (EE), the T-value, the p-value, the variance inflation factors (FIVs), the standard deviation (S) and the determination coefficients (R^2).

In the first model a double logarithmic model has been used for the **turn** variable. In this case, it can be seen that all the FIVs are below the value 5 and the standard error is negligible (about 0.08 in the highest case), so it can be deduced that it is an accurate model. On the other hand, the coefficient of determination is high but should be higher to obtain better explanatory of the variables.

Log(Cons_Elect) = 3,027 + 0,000109 M_2 - 0,000806 n_work + 0,0780 log(turn) – 0,0305 Cons_Term

Term	Coef	EE of coef.	T-value	p-value	FIV
Constant	3,027	0,275	11,01	0,000	
M_2	0,000109	0,000012	8,95	0,000	1,39
log(turn)	0,0780	0,0781	1,00	0,323	1,71
n_work	-0,000806	0,000702	-1,15	0,256	1,50
Cons_Term	0,0305	0,0792	0,39	0,702	1,02

S	R-sq.	R-sq. (adjusted)	R-sq. (pred)
0,276702	72,04%	69,55%	52,27%

Table 3.4: *Results of Model 1 for electricity consumption.*

For the second model, the double logarithmic was applied to the turn and M_2 variables to have a better data fit. It is observed that the results are very similar to the previous case, but a clear improvement and increase in the determination coefficient is obtained, with 96.1%. It seems a very good model to use in the study.

Log(Cons_Elect) = -0,042 + 1,1834 log(M_2) + 0,000282 n_work - 0,0600 log(turn) - 0,0056Cons_Term

Term	Coef	EE of coef.	T-value	p-value	FIV
Constante	-0,042	0,127	-0,33	0,740	
log(M_2)	1,1834	0,0406	29,17	0,000	1,38
log(turn)	-0,0600	0,0303	-1,98	0,054	1,85
n_work	0,000282	0,000259	1,09	0,283	1,47
Cons_Term	-0,0056	0,0297	-0,19	0,850	1,02

S	R-sq.	R-sq. (adjusted)	R-sq. (pred)
0,103401	96,10%	95,75%	89,53%

Table 3.5: *Results of Model 2 for electricity consumption.*

If we use the linear regression model without double logarithmic, we can see how it can be discarded directly due to its low R^2 index compared to model 2.

Log(Cons_Elect) = 3,2978 + 0,000120 M_2 - 0,000216 n_work - 0,000002 turn + 0,0265 Cons_Term

Term	Coef	EE of coef.	T-value	p-value	FIV
Constante	3,2978	0,0668	49,36	0,000	
M_2	0,000120	0,000012	9,61	0,000	1,46
turn	-0,000002	0,000001	-1,13	0,263	1,65
n_work	-0,000216	0,000668	-0,32	0,747	1,36
Cons_Term	0,0265	0,0792	0,33	0,740	1,02

S	R-sq.	R-sq. (adjusted)	R-sq. (pred)
0,275838	72,21%	69,74%	55,29%

Table 3.6: *Results of Model 3 for electricity consumption.*

In model 4, the double logarithmic is used in all variables except **Cons_Term**. There is a great similarity with model 2, but if we look at the standard error in the new variable introduced with logarithm (**n_work**), it is much more superior and would cause a less accurate model

Log(Cons_Elect) = -0,082 + 1,1814 log(M_2) + 0,0050 n_work - 0,0456 log(turn) - 0,0097 Cons_Term

Term	Coef	EE of coef.	T-value	p-value	FIV
Constante	-0,082	0,132	-0,63	0,534	
log(M_2)	1,1814	0,0422	27,96	0,000	1,46
log(turn)	-0,0456	0,0353	-1,29	0,204	2,44
log(n_work)	0,0050	0,0507	0,10	0,922	2,46
Cons_Term	-0,0097	0,0298	-0,32	0,747	1,01

S	R-sq.	R-sq. (adjusted)	R-sq. (pred)
0,104740	95,99%	95,64%	92,19%

Table 3.7: *Results of Model 4 for electricity consumption.*

Finally, concerning with electricity consumption and the last results, it can be concluded as the most explanatory model is the second model, which presents a positive constant elasticity in the variables **M_2** and **turn**. Applying the logarithm to these variables allows to reduce the standard error and to give a better quality with respect to other linear regressions.

The final model chosen is shown below and its normal probability graph in Figure 3.5:

$$\text{Log(Cons\_El)} = -0{,}042 + 1{,}1834 \cdot \text{Log(M\_2)} - 0{,}06 \cdot \text{Log(turn)} + 0{,}000282 \cdot \text{n}_{\text{work}} - 0{,}0056 \cdot \text{Cons\_Term} \quad (3.2)$$

In Fig. 3.5, the data points are relatively close to the adjusted normal distribution line (the continuous intermediate line on the graph). The p-value is greater than the significance level of 0.05. Therefore, the null hypothesis that the data follow a normal distribution cannot be rejected.

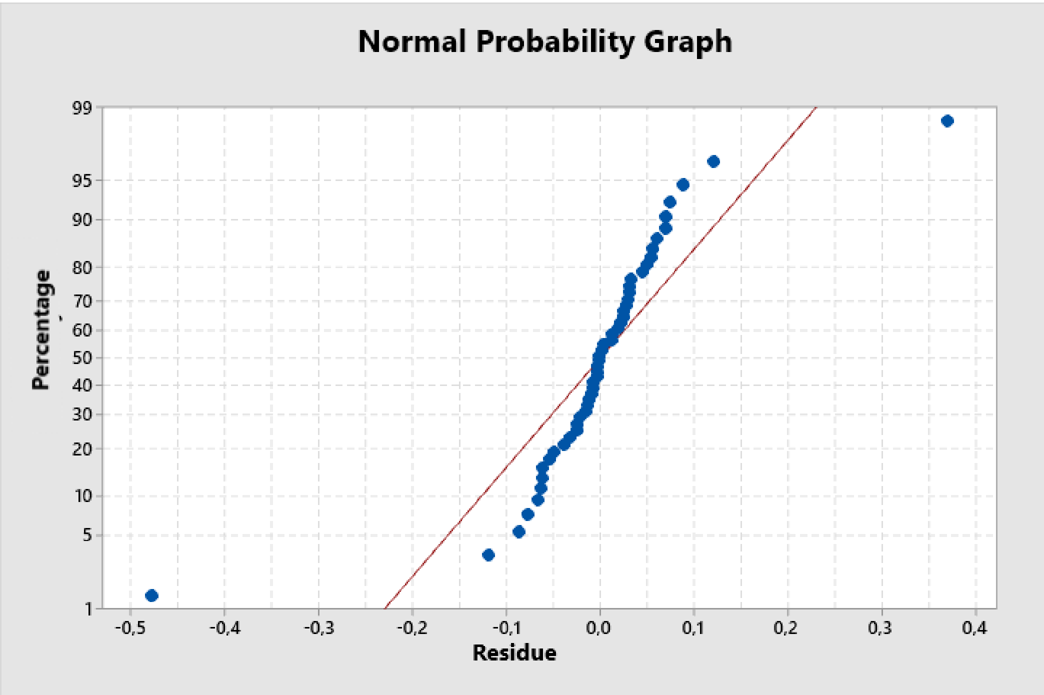


Figure 3.5: *Normal probability graph of Model 2 for electricity consumption.*

The residue versus fit graph in Fig 3.6, serves to verify the assumption that the residues are randomly distributed and have a constant variance. Ideally, the points should be randomly located on either side of the 0, with no detectable patterns in the points. In this case, the criteria for a suitable pattern are met.

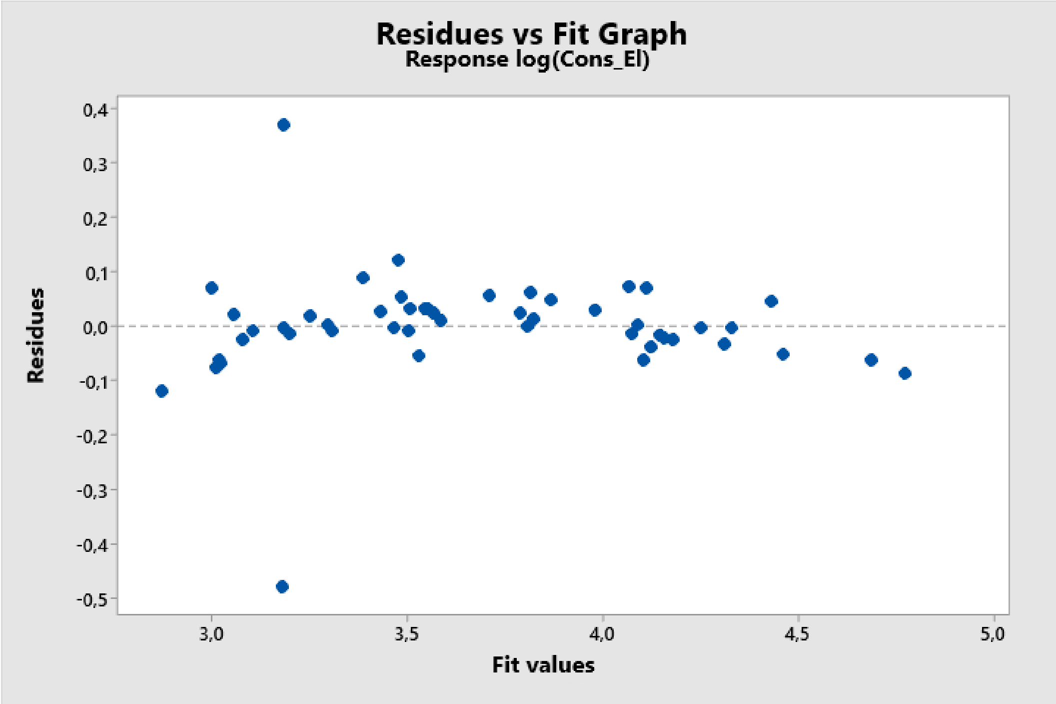


Figure 3.6: *Statistical Waste of Model 2 for electricity consumption.*

As discussed previously, the choice of the logarithm is made for the variables **M_2** and **turn,** and the hours worked have no explanatory power in the estimation of electricity consumption due to the correlation with **n_work**. However, the surface area of the company (**M_2**) has an explanatory power. And here it does make more sense, because as the surface area of the company increases, more machines and electrical equipment are available, a higher use of these elements and a more frequent movement of workers through all the areas of the company. In terms of figures, a 1% growth in the surface area of the company increases electricity consumption by 1.18%.

Model 2 has a remarkably high coefficient of determination (96.10%) and also the lowest selection criteria. Its validation is the proof that $F_C = 75.43 > F_{tab} = 1.45$, obtained for 50 equations (each one for every data's company) and four variables studied.

Following the sensitivity analysis, it is also observed that the variable number of workers (**n_work**) is statistically insignificant but showing a significant impact on electricity consumption and an explanatory power even with a rate of 0.028%. It means as more workers, more movement in the factory and more equipment using electrical energy. Remember that this variable do not have logarithm and for example, if there is a 1% growth therein, it will increase the electricity consumption by approximately 1%.

In the case of thermal consumption (**Cons_Term**), the industrial buildings that have heat sources to generate energy, such as natural gas burners, with a 1% growth of this variable, it help to reduce electricity consumption by 1.01%, because the rate in the regression is -0.56%. This could be due to the fact that not as much electrical energy is used in areas that have equipment like this.

Concerning the company's turnover variable (**turn**), when the company is invoicing more, it will consume less. In any case, having the logarithm applied, a 1% growth in invoicing would simply cause a 0.06% decrease in electricity consumption. In conclusion, this model justifies that invoicing is irrelevant in electricity consumption because for example, a company with facilities that could be smaller such as commercial enterprises or small sellers can expect to charge higher amounts and not consume as much energy.

Water consumption model

To determine the water consumption of industrial companies, the same analysis has been carried out as in the previous section. The different results and models can be looked up in the tables located in the Appendix D.6, concretely in the Statistical approach.

In Table D.3, the results of the definitive model (model 1) can be obtained, including the coefficients of the regression (β_k), the standard error of the coefficients (EE), the T-value, the p-value, the FIVs, the standard deviation (S) and the determination coefficients (R^2). Following is the model 1 chosen and contains the double logarithm for the variables **M_2**, **turn** and **n_work**.

$$\text{Log}(\text{Cons}_{\text{H2O}}) = 0{,}857+0{,}489\cdot\text{Log}(\text{M}_2)+0{,}167\cdot\text{Log}(\text{turn})+0{,}174\cdot\text{Log}(\text{n}_{\text{work}})\text{-}0{,}112\cdot\text{Cons}_{\text{Term}} \tag{3.3}$$

In Fig. 3.7, the data points are relatively close to the adjusted normal distribution line (the continuous intermediate line on the graph). The p-value is greater than the significance level of 0.05. Therefore, the null hypothesis that the data follow a normal distribution cannot be rejected.

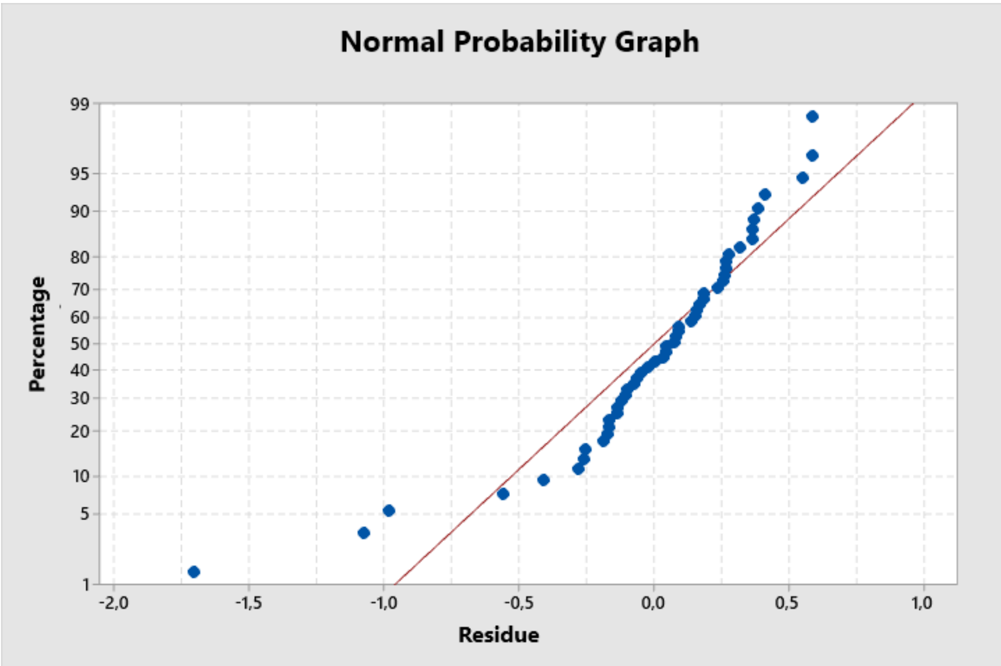


Figure 3.7: *Normal probability graph of Model 1 for water consumption.*

The residue versus fit graph in Fig. 3.8, serves to verify the assumption that the residues are randomly distributed and have a constant variance. Ideally, the points should be randomly located on either side of the 0, with no detectable patterns in the points. In this case, the criteria for a suitable pattern are met.

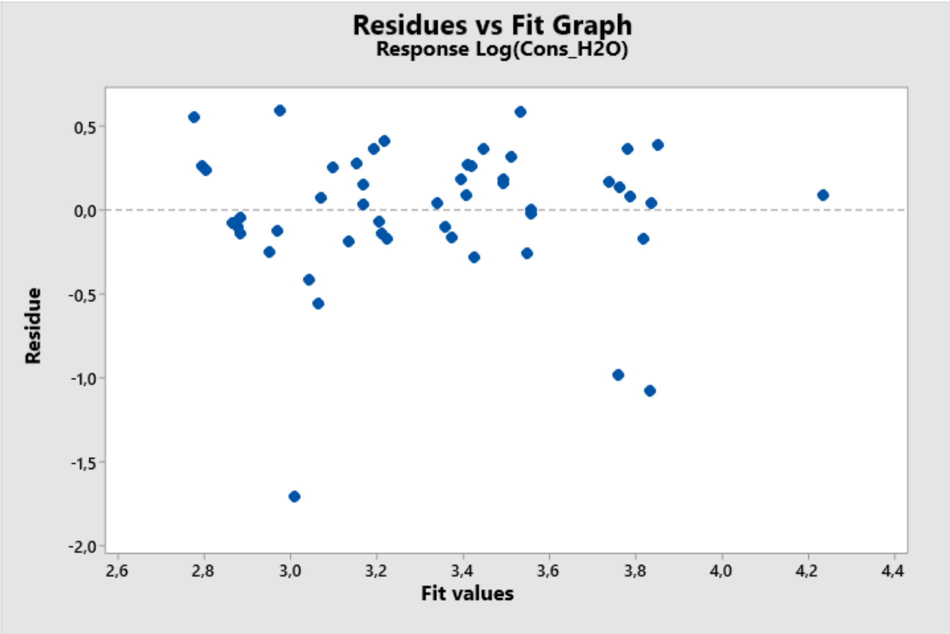


Figure 3.8: *Statistical waste of Model 1 for water consumption.*

All models in general do not have a very high determination coefficient (<40.84%), although the selection criteria are low. The logarithm is chosen for the variables **M_2**, **turn** and **n_work**. As commented previously, the hours worked have no explanatory power in the estimation of water consumption due to the correlation with **n_work**.

However, the surface area of the company (**M_2**) has an explanatory power. Indeed, it makes more sense here, because as the surface area of the company increases, more valves and water points are available, a higher use of these elements and a greater circulation of water throughout all the areas of the company. In terms of figures, a 1% growth in the surface area of the company increases water consumption by 0.49%.

Following with the sensitivity analysis, it is also observed that the turnover variable (**turn**) is statistically significant, showing an important impact on water consumption and an explanatory power at the level of 0.17% by each 1% growth of turnover. As a result, increased turnover leads to the use of facilities and, indirectly, to increased water consumption.

In the case of thermal consumption (**Cons_Term**), industrial buildings that have heat sources to generate energy, such as natural gas burners, help to reduce water consumption by -1,29% (by each 1% growth of thermal consumption) because traditional heating systems are not used as in homes, but rather air conditioning for large areas.

Concerning the variable of number of workers in the company (**n_work**), it is observed that it is statistically significant showing an important impact on water consumption and an explanatory power at the level of 0.17% (by each 1% growth of number of workers). As more workers, more movement in the factory and more use of the facilities that supply water.

It should be noted that the regressions developed are an additional method for calculating electricity and water consumption for industrial buildings, but in this thesis, **the actual consumption data** have been used for the following sections.

3.4 Water Distribution Networks of Area

The hydraulic map provided by the water company of the city of Granollers, will allow a realistic analysis of the flow rates and pressures in the connections of the companies of the industrial areas. Furthermore, the topographic map of the area has been studied in order to assign an altitude to all the points needed for the study and locate the pressure height in each case.

The hydraulic map is defined by a caption with the different information of the pipes that form it and other types of hydraulic elements such as tanks, hydrants, pumps, turbines. To obtain more information about these elements, the hydraulic map will not be enough and it will need information from a topographic map to know the height of the pipe nodes, as well.

A summary of the hydraulic scheme is shown on a larger scale in Appendix F.

3.4.1 Tank

The deposits are defined with the scheme and notation shown in Fig. 3.9, where are normally found in all areas of difficult access or high altitude.

Figure 3.9: *Tank viewed from software Google Earth and its symbol in the hydraulic map.*

In this case, it is located at the maximum altitude of the city, about 170 meters, has a diameter of 20 meters and a volume of approximately 2000 m^3. From these data, the height of the tank has been calculated ($H = 6{,}37\ m$) with the following equation $V = \frac{\pi \cdot \emptyset^2}{4} \cdot H$.

3.4.2 Types of pipes

The water pipes in the hydraulic map are defined by the following caption according to material type and diameter size:

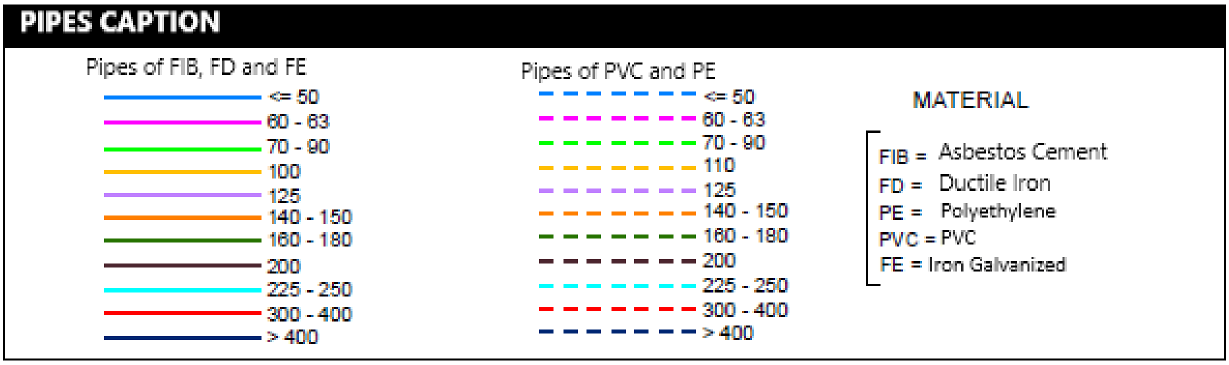


Figure 3.10: *Pipes caption that shows different types of diameter (mm) and materials.*

The main materials, shown in Fig. 3.10, are asbestos cement (FIB), ductile iron (FD), polyethylene (PE), PVC (PVC) and iron galvanized (FE). The colours of the straight lines are used to determine the diameter for FIB, FE and FD materials, while the dotted lines are used for synthetic materials (PE and PVC).

3.4.3 Other elements

In the hydraulic map there are other elements drawn with the scheme in Fig. 3.11.

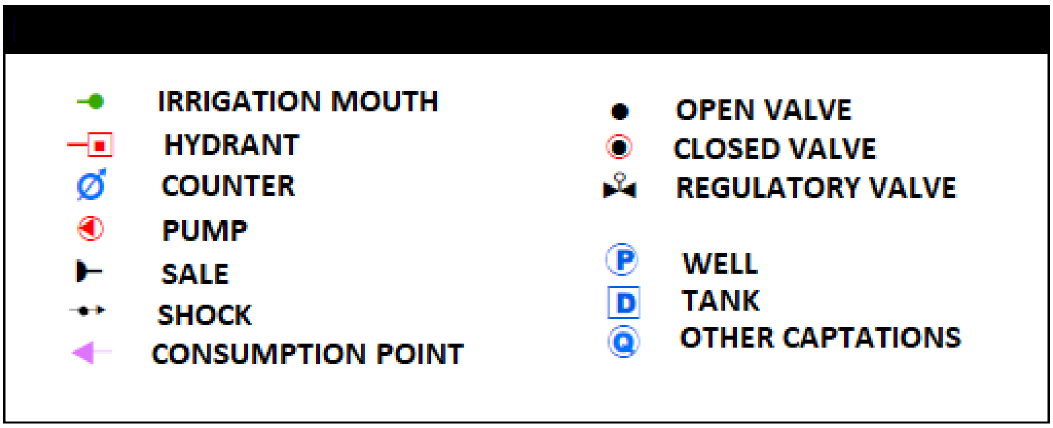


Figure 3.11: *Types of elements in the hydraulic map.*

Only the pumps, the consumption supply, the hydrants and the collection tank, shown in the Fig. 3.11, have been considered for the model.

3.5 Solar Potential of Area

3.5.1 Irradiation Data

The information of the daily global solar irradiation (horizontal component) of the meteorological station closer to the industrial areas has been compiled, provided by the Servei Meterològic de Catalunya[8]. It is available for 2018 and until November 2019.

The panels will be placed according to two indices, orientation and inclination. Both are defined by the coordinates (latitude and longitude), the azimuth angle and the upper sun peak of the location where the installation will take place.

As we have the freedom to adjust the angle of azimuth, evidently and for our latitudes, we will determine the azimuth at 0°, i. e., the southern orientation, because the sun peaks above the southern part of the zenith throughout the year and divides the path of the sun daily into two perfect depths.

If the solar panel has been installed with an azimuth of 0° (Southern exposure), the appropriate height will be the halfway between the maximum and minimum height of the upper sun peak in relation to the location where the solar panel is installed. But in this case, and as it is necessary to guarantee the energy supply in the worst case, it is necessary to make the calculations with the highest sun culmination (h) in the most unfavourable case (December 21, winter solstice). In this date, the panels can collect the maximum energy in this moment of the year when there are less sun hours.

Defining latitude as symbol **Φ**, if it is located at a mid-latitude (**Φ** = 41,60°) and the 21st of December:

a) The sun rises almost to the southeast (Azimuth = 304° 14' 55''), the upper peak is 21° 33' and it sets almost to the south-west (Azimuth = 55° 45' 5''). The day has a duration of 8 h 34 min 21s in solar time.
b) Shadows are never projected southwards at the time of the sun's upper culmination.
c) The sun continues its path by increasing the right ascension and decreasing its declination until it reaches the value of - (23° 27').

In the particular case of the industrial areas of Granollers, the ideal position of the module is defined in Table 3.8.

CONCEPT	VALUE
Inclination of panels, β	41°
Azimuth of panel superficies’, γ	0°

Table 3.8: *Optimal orientation of the photovoltaic modules.*

This is an average value, between the optimum tilt for the winter months (52° to 63°) and the summer months (17° to 29°). As the consumption per month is not available, it is difficult to know whether to opt for the winter solstice or the summer solstice.

[8] Meteorological institute of the Catalonia’s region, Spain. Provides information about weather and meteorological phenomena.

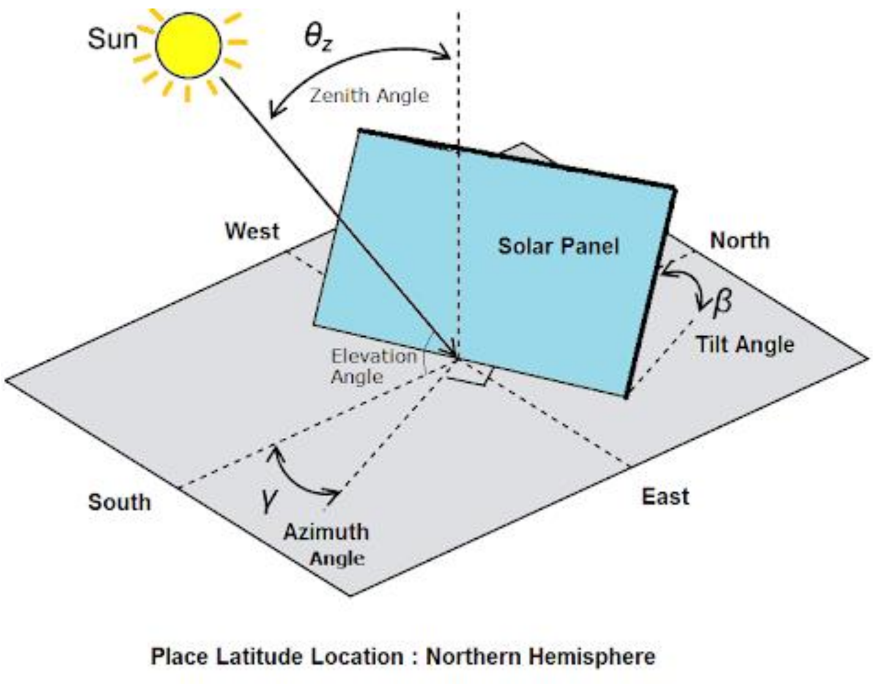


Figure 3.12: *Solar angles used in power calculation for photovoltaic modules.*

In Figure 3.12, is shown all angles used in the next section to calculate each parameter to obtain effective solar irradiance and irradiation of the zone.

3.5.2 Final Solar Irradiance and Radiation

The HDKR Model, located in Appendix E, has been applied to all days of the horizontal solar irradiation information provided in Appendix B, and this has allowed a monthly average to be made in the Table 3.9. This model obtains the effective solar irradiance or radiation through the data measured by a weather station.

	Gt [W/m²]	Gt,eff [W/m²]	It [MJ/m²·day]	It, eff [MJ/m²·day]
January	94.9	85,7	8.2	7.4
February	101.7	91,9	8.8	7.9
March	180.1	162,7	15.6	14.1
April	208.4	188.2	18	16.3
May	225.5	203.6	19.5	17.6
June	275.2	248.6	23.8	21.5
July	283.3	256	24.5	22.1
August	221	199.6	19.1	17.2
September	186.3	168.2	16.1	14.5
October	123.8	111.8	10.7	9.7
November	79.6	71.9	6.9	6.2
December	82.2	74.2	7.1	6.4

Table 3.9: *Final table of solar irradiances and daily radiation by month.*

Figure 3.13 compares the irradiance obtained from the meteorological station ($G[pyro802]$), the total irradiance calculated from the HDKR model (G_T) and finally the effective irradiance ($G_{t\ eff}$) that would be the closest to the real one from the transmittance coefficients. The same values are obtained for the global radiation but in units of energy. The energy graph is not shown as it is very similar to the irradiance graph Fig. 3.13 (same shape) but with the smaller axes.

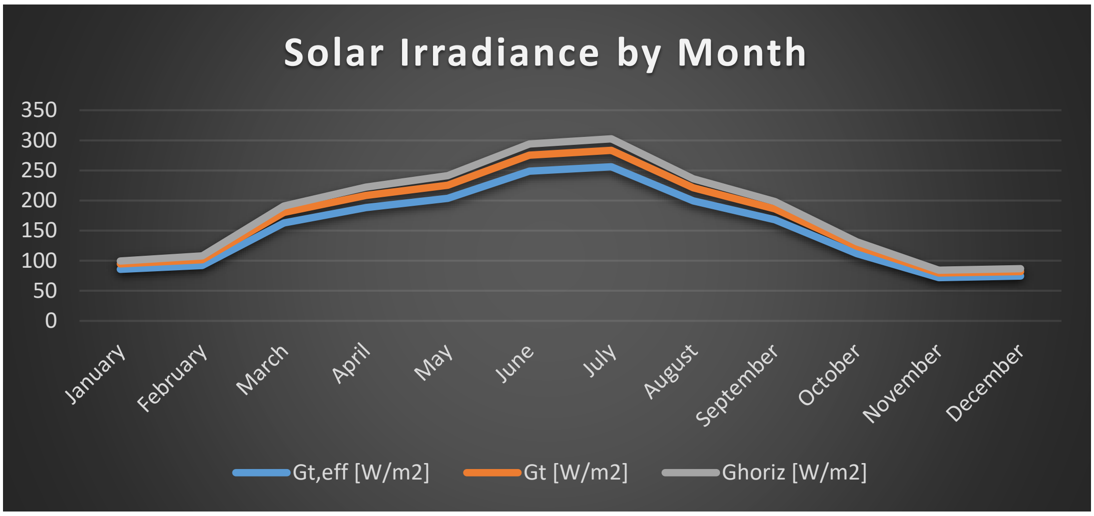


Figure 3.13: *Comparison of different type's solar irradiance of Granollers by month.*

It can be seen that for the most unfavourable month, i.e. November, a radiation of 6.21 MJ/m^2 and a peak solar hour (HSP) of 2.49 are obtained with an atmospheric correction value (f_{atm}) of 95% and a k-factor (k) according to the zone of 1.52, which is shown in the equation 3.4. This factor shows us the capacity that is going to generate a solar panel per day, so if we have to design panels and storage system with batteries, we will have to consider it.

$$HSP = I_{t,eff} \cdot k \cdot\ f_{atm} \cdot 0.2778 \tag{3.4}$$

$$He = \frac{I_{annual} \cdot A_{PV}}{P_{PV}} \tag{3.5}$$

$$E_{annual \cdot 1\ Panel} = He \cdot P_{PV} \tag{3.6}$$

The average annual irradiation is 1359.61 kW-h/m2, while the daily irradiation is 3.72 kW·h/m^2. This means that for a panel with a utilization factor of 15% (efficiency), the real and annual energy ($E_{annual \cdot 1\ Panel}$) that would give per square meter of panel, using Eq. 3.6, would be 203.94 kW·h/m^2. In this case, using the total hours that panel will operate (He) during a year, calculated with Eq. 3.5, and the power of the panel (P_{PV}). Eq. 3.5 is defined by annual radiation of the zone (I_{annual}), the area of the panel (A_{PV}) and its power. For example, with a 250 Wp panel measuring 1.65 x 0.994 m, you would be able to generate a total of 334.48 kW·h/year and operate at about 1337.93 hour/year.

3.5.3 Roofs Inclination

A key factor in the placement of photovoltaic panels is the inclination of the roofs. It is important to be clear that the position needs to be optimised for a good use of the energy and to ensure that the installation is not deficient in terms of costs.

To do this, it is necessary to know that depending on the inclination of the roof, more or less energy can be used, because more or less panels will be placed, depending on the avoidance of shadows. This is related to the concept of occupation where if you want to place the panels at 41°, they will occupy less surface area if the roof is inclined the same degrees and more each time the roof is less inclined. The concept of occupation (A_{oc}) is related in the Eqs. 3.7, 3.8 and 3.9.

Assuming that the panels will be placed at 41°, with a roof inclination of 41°, it will allow to obtain an annual energy per meter of ground of 246.39 kW·h/ m^2, while for a roof with a 20° inclination of 159.73 kW·h/ m^2. In the case of having flat roofs (0°), the placement of these panels will have to be much more separated so we will have an energy of 85.89 kW·h/ m^2.

The occupancy of the panels is given by the following schemes and they have been obtained by source [9] **(Furró, 2019)**. In addition, Eqs. 3.7, 3.8 and 3.9, also obtained from this source, allow us to define the placement of the solar panels, preserving a separation between them (parameter d), to avoid shadows, i.e, with a percentage of 0% of shadows in the installation. Finally, the variables will be defined below.

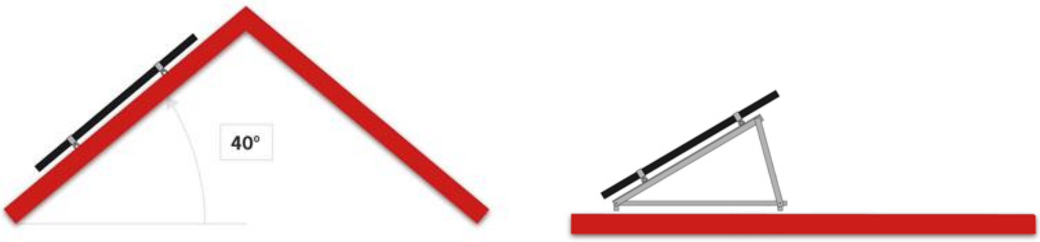


Figure 3.14: *Types of roofs to place the PV panels (Flat and titled at 40°).*

$$A_{oc} = L \cdot N_s \cdot \left(w \cdot N_p \cdot \cos 41° + \frac{w \cdot N_p \cdot \sin(41°)}{\text{tg } 20°}\right) \quad (3.7)$$

$$A_{oc} = L \cdot N_s \cdot \left(w \cdot N_p \cdot \cos 41° + d\right)$$

$$d = \frac{h \cdot w \cdot N_p \cdot \sin(41° - 20°)}{\text{tg } 20°} \quad (3.8)$$

$$A_{oc} = \left(w \cdot N_p + 0{,}9\right) \cdot \cos 41° \cdot L \cdot N_s \quad (3.9)$$

Where w is the width of the panel, L the length, N_s and N_p the number of panels in series and parallel, respectively and d the maintenance gap or distance between panels.

For example, in the case of having 2 panels in series by 2 branches in parallel, depending on the inclination in each previous scenario, a different surface is occupied, so for roofs of 20° (Eq. 3.8) and 0° (Eq. 3.7)**,** they increase occupancy by 25.45% and 133.38% more than those of 41° (Eq. 3.9)**.** This information is calculated for all the roofs required in the study using basic equations based on trigonometry and estimating that the space between panels named maintenance space is at least 0.9 meters. This value serves to provide the installer with sufficient space to do maintenance work on roofs.

4 PANELS (2x2)	A_{oc} [m²]	% increase
Total Area needed for Roof 41º [m2]	**7,19**	**-**
Total Area needed for Roof 20º [m2]	**9,02**	**+25,45%**
Total Area needed for Roof 0º [m2]	**16,78**	**+133,38%**

Table 3.10: *Occupability of the case 4 x 4 panels by type of roof.*

Concluding this chapter, it can be seen in Table 3.10, how the 41-degree tilt not only improves the efficiency of energy collection during the year, but also allows the occupancy of the roof to be optimised, always avoiding shadows between panels.

Chapter 4

4 Shared Projects

In this section will be discussed about Shared Projects, which are all those connections or installations between users or entities that allow the creation of an energy community. Above all, it will focus on the agents involved, the technical and regulatory limits and finally energy optimisation through Matlab.

4.1 Creating Energy Communities

4.1.1 Procedure and Technical Limits

To create an energy community, a thorough study of the standards and laws that make up the technical guides of the country where the installation will be located is required. For this reason, the steps to be taken to do so have been broadly defined in accordance with the professional guide for self-consumption [8]:

1- Sign a contract with an agreement on energy distribution criteria (β) between consumers and producers as explained in the chapter on Prior Regulatory Requirements.
2- Sign a simplified compensation contract between producer and consumers, in the case of the existence of surpluses or between consumers, without surpluses.
3- Send the documents to the distribution company for each consumer, applying the same self-consumption modality for all.

In this research, the system in which there are several associated consumers will be evaluated, therefore, the connection will be made in the **internal network**, upstream of the supply meter of each consumer. In most cases, the modality WITH surplus will be used, where there will be two subjects: producer and consumers, which may be different individuals or legal entities. In the modality WITHOUT surpluses, there is no producer.

The self-consumption facility (PV in the example) has a net-generation bi-directional meter, because on the one hand, the surplus energy from the PV panels is injected into the power grid and on the other hand, the electricity from the grid is fed into the consumption. Each associated consumer has only one meter, being the supply one, which will record the measurement of all the energy that reaches each consumer. In the mode WITHOUT surplus, there is an anti-spill system noted in Fig. 4.1, which prevents the transfer of energy to the grid.

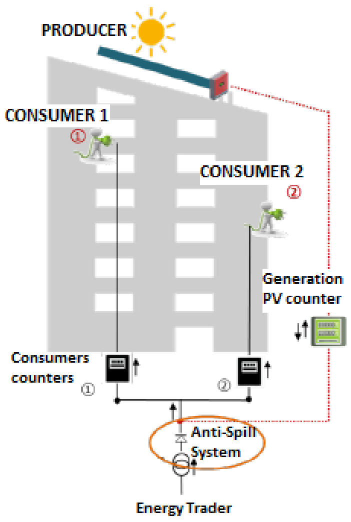


Figure 4.1: *Basic installation model for energy community with producer and consumers policy.*

In order to be eligible for compensation, the generation installation must be renewable and of **P≤100 kW.** The generating installation must be adjusted in order that its generation can satisfy the total consumption of the associated consumers. If it is an installation WITHOUT surpluses, the adequate sizing takes on more importance, because the generation will be adapted to the consumption due to the existence of an anti-spill mechanism, so that if there is no consumption there will be no generation.

The generation in each hour will be as a maximum the total consumption of the consumers connected downstream of the generation, because it is possible that in some moment of that hour the generation will not be able to supply the demanded energy. Ideally, consumers should accommodate their demand to PV generation, in a way that maximizes self-consumption, since that is where the most important savings in the bill are found. When more hourly consumption is paired with hourly PV generation, the more savings will be made.

4.1.2 Operation of Energy Compensation

At the end of the month, the distributor will read the hourly net generation meter of the self-consumption facility (ENGh) and will provide the marketer with all the necessary information for billing and compensation. The distributor will be responsible for billing and compensation of the surplus based on this information. Therefore, for each hour, the distributor:

(i) Allocates the energy generated by the PV to each consumer according to the reported fixed:

$$ENG_{h,i} = \varphi_i \cdot ENG_h.$$

(ii) Compares the individual hourly energy $ENG_{h,i}$ which corresponds to each user with the hourly measurement of their individual supply meter (individual hourly energy consumed).

If the individualized hourly energy consumed (in that hour) is greater than $ENG_{h,i}$ then the individualized hourly self-consumption ($E_{auth,i}$) will be $ENG_{h,i}$. This means that the bill for energy consumed from the network (in that hour) will be the hourly meter measurement minus $ENG_{h,i}$. If it is less than the $ENG_{h,i}$ then the bill for network energy (in that hour) will be 0 kWh.

At the end of the month, we will have a certain network consumption for each consumer with all his or her hourly consumption added up. On the other hand, surpluses will have been generated, as there will be hours when $ENG_{h,i}$ is greater than individual hourly consumption, so that all hourly surpluses are valued at their corresponding hourly price and their value is added up. The total surpluses of each associated consumer will be balanced out on their electricity consumption bill, at the end of the billing period.

4.2 Statistical Study Methodology

In this section, a statistical study is carried out to determine in which points or areas of the industrial estates it is more feasible to act and more likely to create energy communities. To do this, it is necessary to determine the number of potential customers who have the potential to generate energy (Generating Leads), the consumers interested in upgrading their energy system and finally to determine the optimal ECs to apply the possible improvements.

This survey has been carried out with a number of observations (N) of 50, companies from the industrial areas Coll de la Manya and Font del Ràdium, from which sufficient information is available to calculate the factors and indices shown below. This information is located in the appendix C.

4.2.1 Generating Leads

The main potential customers will be chosen to be the generators of renewable energy and sell it to nearby companies, to form energy communities. They will also be the main actors who will help promote the solution with their neighbours and potential energy sharing partners.

This idea is shown in the equation 4.1 and it will be promoted in those companies that have a large solar capacity, i. e. enough surface to install photovoltaic panels (solar farm) and also an abusive consumption of energy that allows to reduce CO_2 emissions and the general costs of the company.

$$Pot_{Client\ 1} = Solar\ capacity + Anual\ Electricity\ Consumption \tag{4.1}$$

This equation tries to find the maximum values of the data table obtained from the 50 companies. In this way, the companies with the highest electricity consumption and solar capacity on their roofs will be determined. In Figure C.1 and C.2, there are classifications by solar capacity and annual electricity of all companies used in the study. Their tables listing all values shown in these figures are in the Appendix C. Based on these potential customers, a clustering will be carried out to promote the energy communities of those companies that are less than 500 metres away, a distance marked by the legislation on shared self-consumption.

4.2.2 Consumers Leads

Consumer leads are considered those who will obtain most of their energy from the Generating Leads, although they may also generate some energy for distribution or self-consumption. Their aim is to reduce the costs of the electricity bill based mainly on a need to reduce costs.

To evaluate the Consumers Leads who could use the solution, we based on the electricity cost per capita added to the water cost per capita:

$$Pot_{Client\ 2} = \frac{number\ of\ workers}{electricity\ bill} + \frac{number\ of\ workers}{water\ bill} \tag{4.2}$$

$Pot_{Client\ 2}$ will be the weighting factor that will relate the amount of money spent by the company on salaries and the electricity or water bill. From this, those companies that could generate substantial savings in electricity and/or water bills, if a standalone system or a grid-connected Sharing system is applied will be taken out.

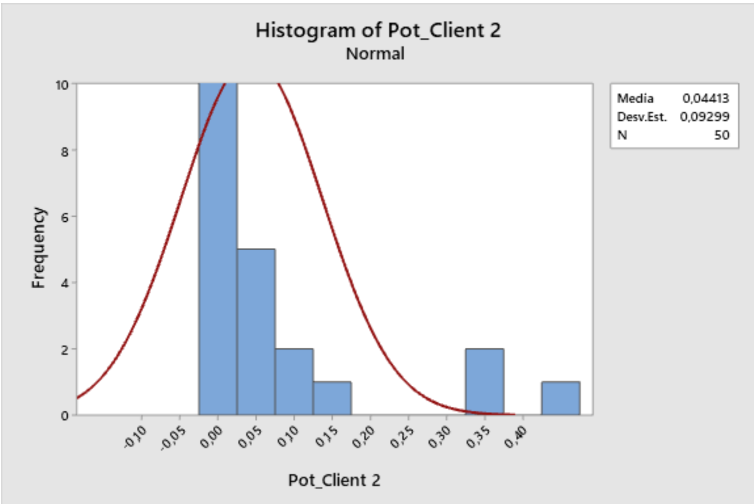


Figure 4.2: *Histogram of Pot_Client 2 index.*

As expected and shown in Fig. 4.2, those companies that the calculated weighting factor tends more to zero, will be potential candidates to apply our solution because when more is the consumption (factor numerator), more will have the capability to reduce costs in electricity bills and therefore allocate that money in the payment of workers' salaries.

A distinction must also be made between those companies that consume a lot of energy and water because they are big companies with many workers, but their waste of resources compared to the salaries of the workers is a very small percentage. In this case, they would no longer be potential leads because they are not interested in making such a huge investment to save on small annual costs that would not be reflected on their balance sheets. In this case, it is studied by comparing two factors located to equations 4.3 and 4.4; salaries and the total sum of consumption (F1) and salaries and company turnover (F2).

$$F_1 = \frac{electricity\ bill + water\ bill}{Salaries} \quad (4.3)$$

$$F_2 = \frac{Salaries}{Company\ Turnover} \quad (4.4)$$

Those companies that are financially solvent will always be considered, i.e., those that have an $F_2<1$, in this case, in Fig, 4.3, this condition is always fulfilled.

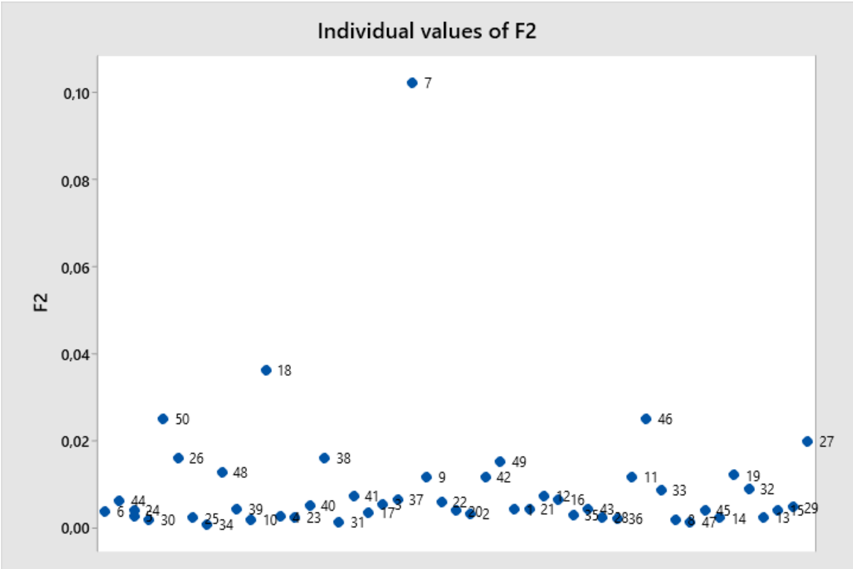


Figure 4.3: *Individual values (number of observations) of factor F2.*

Considering Fig. 4.4, companies where the cost of workers' wages is higher than the consumption of energy and water resources, those with the **highest F_1 are defined as potential candidates**, with a cut-off of F_1=0.02.

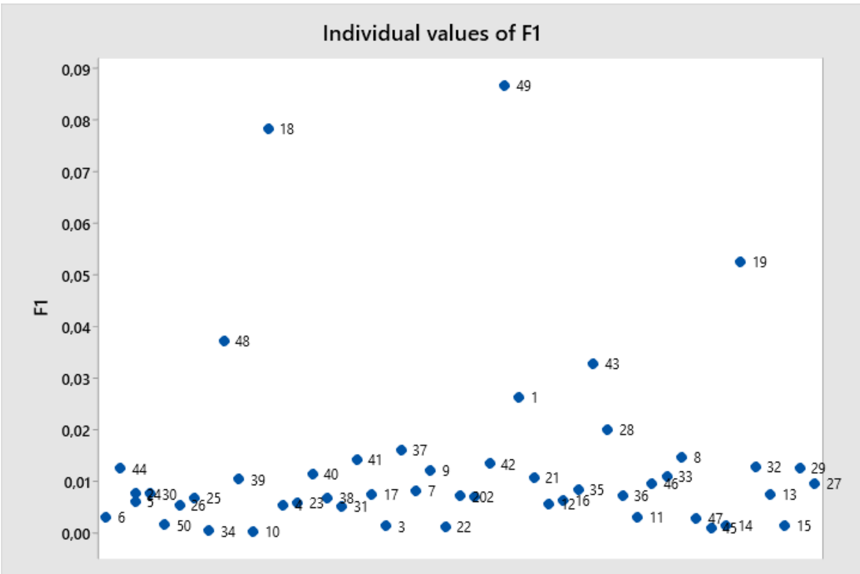


Figure 4.4: *Individual values (number of observations) of factor F1.*

4.2.3 Sharing Groups

First, the idea is to find groups of companies where one has only pairs of companies that are capable of sharing energy. At this point to make more easily the analysis, one considers companies sharing energy coming from photovoltaics installed at each roof and a general micro-turbine. Hence, the set of variables to consider for selection of pairs' energy sharing companies can be:

1. The total electricity consumption of each company: EC_n, where n is the company.
2. The total number of workers in the Company: W_n.
3. The per capita electricity cost for each Company given by: $P_{k\_n} = \frac{EC_n}{W_n}$.
4. The distance between the two companies. Pairs must be neighbors or with only one building between them: $d_{12} \quad [m]$
5. The solar capacity (rooftop area capable to install PV panels) of each company: $S_n \quad [m^2]$

If it is used a general micro-turbine in the energy community of K companies for recovering the hydraulic energy, is necessary to consider these variables as well:

6. The water demand by year of each company: $D_{k\_n} \quad [m^3]$
7. The total water demand of the companies given by: $D_{k\_T} = \sum_{n=1}^{N} D_{k\_n}$ where N is the total number of companies in the energy community.
8. The pressure of the general pipe of the energy community: $p_{k\_T} \quad [mca]$
9. The flow of the general pipe of the energy community: $Q_{k\_T} \quad \left[\frac{m^3}{s}\right]$

To compare each company with the others, following assumptions can be used to decide if a certain pair of companies are adequate for sharing energy or not:

1. The per capita electricity cost of both companies 1 and 2, for example, are "similar", that is, both are good candidates to ask for other sources of energy:

$$\left|P_{k\_1} - P_{k\_2}\right| = \left|\frac{EC_1}{W_1} - \frac{EC_2}{W_2}\right| \leq \varepsilon \tag{4.5}$$

   Sharing energy concept is interpreted as prosumers. Each company can "help" each other mainly when their power load is complementary. For example, one that has a large electricity consumption and other that has low (compared with that having large), but both have similar per capita electricity costs, one can help the other since they do not produce nearly the same energy.
2. The distance between candidate companies to share energy should be approximately between neighbors or in the same block. It is complicated to establish a battery connection

between companies by which a road or mobility zone of the industrial area is crossed. This is why the following constraint is defined with d_{12} in meters and according to the regulations in the section 2.2.2:

$$d_{12} < 500 \tag{4.6}$$

3. It is necessary to have a general pipe that distributes the water to the candidate companies, in order to be able to establish a turbine that will provide extra energy to the system. The total demand of the companies will have to provide enough energy to recover the investment in the turbine and provide a minimum pressure. The minimum consumption pressure for the supply to a point (house or industrial building) is set at between 25 and 30 metres of water column (mWC). This point is obtained by the source [16] **(Ghorbanian, 2016)**.

   For this, it is defined that from the water tank to the turbine the condition of:

$$p_{k\_T} = H_{tank} - H_{turb} \geq 25 \tag{4.7}$$

   This type of restriction will always depend on the turbine chosen in each system (curves $p_{k\_T} - Q_{k\_T}$), which will consequently require an exhaustive prior study of the net head (H) and available flow variables of the companies (Q).

Clustering of observations

To define the groups of the 50 companies studied, a clustering has been applied focused on the number of observations in the sample and taking into account the previous restrictions defined with the variables of minimum supply pressure (p_{k_T}) and cost electricity per capita (P_{k_n}).

Establishing a desired similarity between the observations of 90% to be as close to reality as possible, we specify 7 clusters or groups in the Table 4.1.

Conglomerate 1	**12 observations**
Conglomerate 2	**14 observations**
Conglomerate 3	**12 observations**
Conglomerate 4	**3 observations**
Conglomerate 5	**2 observations**
Conglomerate 6	**6 observations**
Conglomerate 7	**1 observations**

Table 4.1: *Number of observations by cluster or conglomerate.*

Figure 4.5 shows the different groups of companies (observations) and their level of similarity (in percentage) according to the restrictions defined in the previous section. As can be seen, all the groups present a similarity above 60% and the majority have above 85%. This gives a glimpse of a well-done clustering.

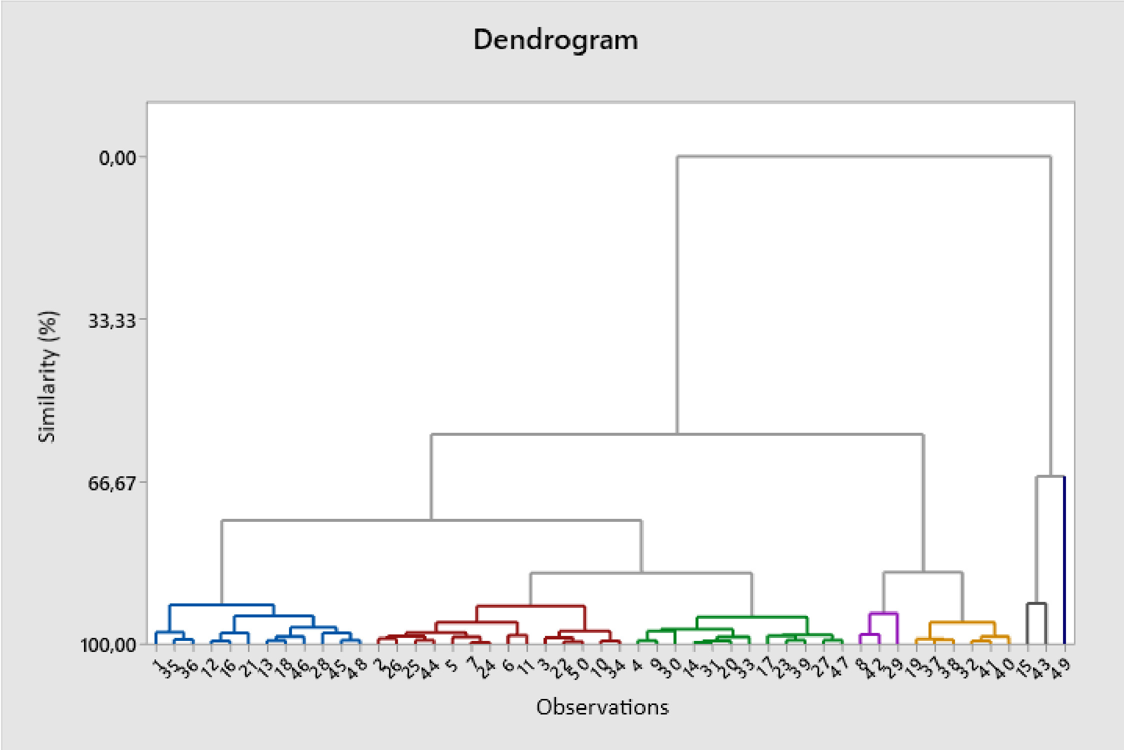


Figure 4.5: *Dendogram study with the clustered observations.*

In each group or conglomerate, one generating lead and several consumers leads will be chosen according to the indexes and restrictions defined above. To simplify the study, only the particular case of an energy community, i.e. a cluster, will be studied. In this way, conclusions can be reached and extrapolated to the other clusters. The observation with the **ID14** number, **Mondelez International S.A.** is chosen as a potential company due to its location in the center of the industrial area, which allows establishing connections with the majority of companies. In addition, its elevation is 143 meters and fulfils the requirement of having a pressure of more than 25 meters of water column in the entrance of the micro-turbine.

It is a member of **conglomerate 3**, so it could join as an energy community with the following 11 companies: **ID04** - TRANSPORTES JUBERA, **ID09** – MAINCA, **ID30** – PINTADOS TECNICOS DEL VALLES, **ID31** – AIRNOU S.L, **ID20** – RELEM, **ID33** – PAVER S.L, **ID17** – INDUSTRIAS PLASTICAS PUIG, **ID23** – GERCO, **ID39** – DUBOSA, **ID27** – COALIMENT GRANOLLERS and **ID47** – MAQUINARIA DARA. Their basic information along with the sector in which they are involved is located in Appendix C.

To discard those that are not feasible options legislatively talking, the distances between the company Mondelez International S.A. and the others are calculated. In Fig. 4.6, the companies are located according to longitude and latitude and it is observed which is the definitive group to study along with the discards for having a distance greater than 500 meters:

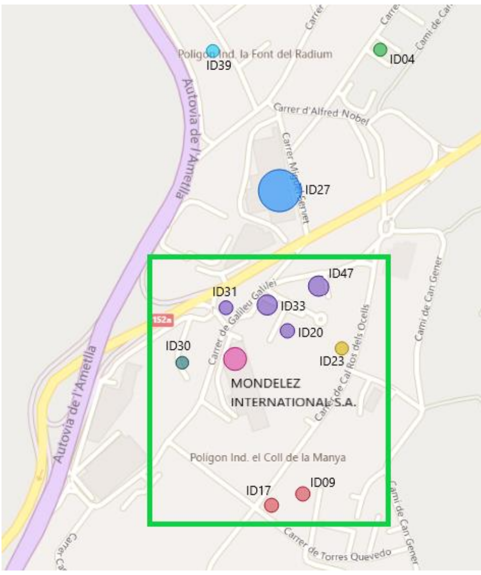


Figure 4.6: *Location of companies related to conglomerate or group 3.*

Once the number of companies has been reduced due to the distance, the indices explained above, Pot_Client 2, F_1 and F_2 are calculated to evaluate which are consumers leads, who will be members of the energy community with the generating lead (ID14).

ID	Comercial Name	Pot Client 2	F1	F2	Distance to ID14
14	MONDELEZ INTERNATIONAL	5,47%	0,05%	46,11%	-
09	MAINCA	6,34%	0,15%	20,51%	350 m
17	INDUSTRIAS PLASTICAS PUIG	3,99%	0,30%	30,56%	300 m
20	RELEM	5,13%	0,26%	26,36%	200 m
23	GERCO	49,97%	0,07%	44,69%	200 m
30	PINTADOS TECNICOS DEL VALLES, SL	4,52%	0,44%	54,24%	20 m
31	AIRNOU SL	5,79%	0,14%	83,50%	100 m
33	PAVER, SL	5,63%	0,44%	11,82%	200 m
47	MAQUINARIA INDUSTRIAL DARA	5,55%	0,07%	80,02%	300 m

Table 4.2: *Factors of the reduced number of companies for the final decision.*

It can be seen that, with only the first index, those with less than 5% can be discarded, i.e. ID17 and ID30.

With the second index (F_1), those companies with a lower index (threshold of 0.07%) will be rejected because they will not save too much money in workers' salaries with the new solution. Therefore, they will not be included in the study ID23 and ID47.

Finally, and because the companies remaining in the study are very similar in terms of index values, it is decided to choose the 3 companies closest to the potential customer generator **ID14 – MONDELEZ INTERNATIONAL S.A**. These are the following and allow us to simplify the definitive sustainable proposal.

ID20 – RELEM / ID31 – AIRNOU S.L / ID33 – PAVER S.L

4.3 Optimization Methodology

To apply what has been previously studied in the field of energy sharing, storage and generation, an optimization problem has been developed to evaluate energetically and economically the future particular cases of energy communities in industrial areas. This model will be applied in the particular case of Chapter 5 on an experimental basis to find overall conclusions on shared self-consumption.

4.3.1 Model Definition

Before formalizing the optimization problem, to understand it, is necessary to define the constants or inputs in the Table 4.4, variables in the Table 4.6 and parameters in the Table 4.3, included in the previous model obtained from the source [7] **(Alvaro-Hermana, 2019)**. In this case, the model has been adapted to one with hybrid generation by means of micro-turbines and photovoltaic panels. This can be seen in the equations, specifically in the generation variables of Table 4.6, where they are defined as g_{TB} for micro-turbine generation and as g_{PV} for photovoltaic. Table 4.5 shows the consequences of the problem variables.

Parameters	**Description**
k	Consumer index
t	Time index

Table 4.3: *Parameters of Eqs. (4.8) – (4.13).*

Inputs	**Description**
K	Number of consumers.
T	Number of periods.
D(k, t)	Consumption of consumer k at time t.
G(t)	Total generation at time t.
$C_D(t)$, $C_E(t)$	Cost of electricity demand and surplus at time t.
B	Battery capacity.
η, μ	Battery efficiency and depth of discharge.

Table 4.4: *Constants of Eqs. (4.8) – (4.13).*

Consequences	**Description**
b(t)	Battery charge at time t.
d(k, t)	Net demand of consumer k at time t.
e(t)	Global system surplus at time t.

Table 4.5: *Results of Eqs. (4.8) – (4.13).*

Variables	Description
$b_e(t)$	Electricity from global battery pack to surplus at time t.
$b_k(k, t)$	Electricity from global battery pack to consumer k at time t.
$g_{PV,b}(t)$, $g_{TB,b}(t)$	PV and Turbine generation to battery at time t.
$g_{PV,e}(t)$, $g_{TB,e}(t)$	PV and Turbine generation to surplus at time t.
$g_{PV,k}(k, t)$, $g_{TB,k}(k, t)$	PV and Turbine generation to consumer k at time t.

Table 4.6: *Variables of Eqs. (4.8) – (4.13).*

The purpose of the function to solve the optimization problem is to minimize the costs of the electricity bill for all consumers separately in the energy community. It is defined as Eq. 4.8, which aims to minimize the overall consumption costs of the energy community ($\sum_{k=1}^{K} d(k, t)$) and maximize the benefits of the system's surplus ($e(t)$).

$$\min \sum_{t=1}^{T} \left(C_D(t) \cdot \sum_{k=1}^{K} d(k, t) - C_E(t) \cdot e(t) \right) \quad (4.8)$$

In addition, Eqs. 4.9 to 4.13 are the present equations in the problem and the first one is defining the distribution of generation through the system. In this case, it will be formed by the generated energy that is distributed to the battery, the one that is distributed to the consumptions and finally that which is injected to the electric network as surplus.

$$G(t) = g_{PV,b}(t) + g_{TB,b}(t) + g_{PV,e}(t) + g_{TB,e}(t) + \sum_{k=1}^{K} g_{PV,k}(k, t) + \sum_{k=1}^{K} g_{TB,k}(k, t) \quad (4.9)$$

Equation 4.10 is defining the total net demand of each consumer in the energy community and this integrates the electricity consumption minus the energy generated by the turbine, the one generated by the photovoltaic installation and the energy used that was stored in the battery.

$$d(k, t) = D(k, t) - g_{PV,k}(k, t) - g_{TB,k}(k, t) - \eta \cdot b_k(k, t) \quad (4.10)$$

It is important to define the equation on the battery in Eq. 4.11. In this case, it will be the energy that was already stored in the previous period, added to that which has been generated and will be stored in this period, minus the energy consumed by the consumers and which will be injected into the electricity grid in the current period.

$$b(t) = b(t - 1) + \eta \cdot g_{PV,b}(t) + \eta \cdot g_{TB,b}(t) - \sum_{k=1}^{K} b_k(k, t) - b_e(t) \quad (4.11)$$

In order to limit the surplus to the electrical network, equation 4.12 is necessary, where it says that the surplus will be formed by the part generated by the turbine and the photovoltaic installation that is injected into the electrical network and the part stored in the battery that is also to be sold.

$$e(t) = g_{PV,e}(t) + g_{TB,e}(t) + \eta \cdot b_e(t) \quad (4.12)$$

Finally the constraint 4.13, allows limiting the capacity of the battery so that it always has a minimum of stored energy marked by the value μ.

$$\mu \cdot B < b(t) < B \quad (4.13)$$

Due to the complexity of the problem, useful approach could be that the initial battery charge, b(0) is negligible because it is a way of continuing the problem in a more simplified form and thus not taking into account the initial impact.

4.3.2 How to study the results

The results obtained could be analysed separately by two energy policies:

Demand-dependent exchange: related to the optimization of the electricity demand and therefore the total saving of the system is shared equally among all consumers. Demand-dependent sharing is a policy whose aim is to optimize the local relation between generation and demand. This is obtained by giving freedom in the distribution of energy among the owners, instead of sharing the economic benefits of the system. Thus, the amount of money saved by the system is compared with the base case (no generation and no battery) and its difference is shared equally among users. The bill paid by the owners is equal to their bill in the base case minus their proportional share of the benefits. The payment of the equipment will be calculated as a cost for the complete energy community as a whole, although each company will have to take care of the equipment in its area. Therefore, no new restrictions are needed for the system previously described (Eqs. 4.8 - 4.13) and a post-processing of the bill is required for determining the individual electricity cost for the owners.

Proportional distribution of the energy: all consumers of the EC receive the same amount of energy per hour and they distribute energy savings proportionally and separately. Because this policy introduces new restrictions, the gains of the system are lower than the demand-dependent sharing. Since it simplifies the calculation of each consumer's bill, it is easier to implement. This type can be mathematically expressed by equation 4.14.

$$\sum_{t=1}^{T'} g_{PV,k}(k1, t) + \sum_{t=1}^{T'} g_{TB,k}(k1, t) + \eta \cdot b_k(k1, t) = \sum_{t=1}^{T'} g_{PV,k}(k2, t) + \sum_{t=1}^{T'} g_{TB,k}(k2, t) + \eta \cdot b_k(k2, t)$$

$$\forall\, k1, k2 \in K \quad (4.14)$$

Equation 4.14 is showing that all members of the energy community will be supplied with the same amount of electricity at each instant of time. For example, if in one year, 1000 kWh is generated and there are four members, 250 kWh of renewable energy will be distributed to each member. So, each consumer perceives the same amount of energy during a certain period of time T'. T' is the number periods analysed in the problem and K is the number of consumers sharing in the installation.

In the results, it is used the energy policy of Demand-dependent exchange and this one is compared with No-Sharing and no Self-consumption. In addition, different price options could be assessed for the sale of surplus energy, always including the next restriction, cost of surplus < cost of demand (C_E<C_D).

Finally, the self-consumption's retribution must be also examined. Three schemes are proposed here: net metering, in which the electricity surplus is priced at the retail electricity price (C_E = C_D); net billing, in which the electricity surplus is priced at the retail electricity price, and the third one the exclusive self-consumption, in which electricity surplus has no value (C_E=0). In Spanish legality, is not possible that net metering work in any energy system, so it will not be analysed.

With these comparisons, it is expected to obtain a criterion on the net energy price of the energy community where it should not vary in any model and an acceptance of the use of batteries clearly providing economic advantages to consumers. Finally, it is necessary to demonstrate that the use of a hybrid system with micro-turbine in the general pipe, adds value to the solution.

4.3.3 Model Design

This optimization problem has been designed using Matlab software and more specifically with the FMINCON module, a non-linear programming solver that searches for the minimum of a problem specified by constraints and equations 4.15.

$$\min \boldsymbol{f(x)} \quad (4.15)$$

$$\boldsymbol{c(x) \leq 0} \quad (4.15.a)$$

$$\boldsymbol{ceq(x) = 0} \quad (4.15.b)$$

$$\boldsymbol{A \cdot x \ \leq b} \quad (4.15.c)$$

$$\boldsymbol{Aeq \cdot x = beq} \quad (4.15.d)$$

$$\boldsymbol{LB \ \leq x \leq UB} \quad (4.15.e)$$

Where (4.15.a) and (4.15.b) are non-linear constraints, (4.15.c) and (4.15.d), are linear and (4.15.e) are bounds. These variables are defined in two sections below called matrices.

Inputs

In order for the optimization process to work, it is necessary to give it the constants defined above on Table 4.4 as program inputs. Each one will have some sizes according to the number of companies that we put to the problem (K) and number of moments of time (T).

```
T: Total number of periods
```

Format: value in hours, months or years.

```
K: Total number of companies
```

Format: value.

```
B: Battery capacity
```

Format: value in A·h.

```
u: Depth of discharge of battery
```

Format: value.

```
n: Battery efficiency
```

Format: value.

```
D: Matrix of consumption
```

Format: matrix size (K x T) in kWh.

```
G: List of total generation (Turbine and PV)
```

Format: matrix size (T x 1) in kWh.

In this case, the generation is calculated separately (PV and turbine), but the program groups it by the sum in the constant G.

```
Ppv: Total power PV panels
```

Format: matrix size (T x 1) in kW

```
Ptb: Total power micro-turbine
```

Format: matrix size (T x 1) in kW

```
Cd: List of electricity cost
```

Format: matrix size (T x 1) in € or $.

```
Ce: List of surplus cost
```

Format: matrix size (T x 1) in € or $.

Variables

The problem is solved with eight variables, instead of the eleven previously defined, to simplify programming. The three variables deleted, will be explicitly introduced in the first three solutions of the problem: $x(1), x(2)$ and $x(3)$ and it is shown in Eqs. 4.16.a, 4.16.b and 4.16.c. Therefore, they will combine the energy of the turbine and the energy of the photovoltaic panels in the same variable and then, to define the percentage of hydraulic and photovoltaic energy, it will be divided according to the percentage of the power installed (P_{PV} and P_{TB}) calculated in section 5.1.1 and 5.1.2. This percentage is defined differently according to each project or case, as seen in chapter 5. The other problem solutions are defined in the program as the equations 4.16.d, 4.16.e, 4.16.f, 4.16.g and 4.16.h.

$$SOLUTION \underset{min}{\Longrightarrow} \boldsymbol{x} = [x(1), x(2), x(3), x(4), x(5), x(6), x(7), x(8)] \quad (4.16)$$

$$x(1) \xrightarrow{yields} \mathrm{g_b(t) = g_{PV,b}(t) + g_{TB,b}(t)} \quad (4.16.a)$$

$$x(2) \xrightarrow{yields} \mathrm{g_e(t) = g_{PV,e}(t) + g_{TB,e}(t)} \quad (4.16.b)$$

$$x(3) \xrightarrow{yields} \textstyle\sum_{k=1}^{K} \mathrm{g_k(k, t)} = \sum_{k=1}^{K} \mathrm{g_{PV,k}(k, t)} + \sum_{k=1}^{K} \mathrm{g_{TB,k}(k, t)} \quad (4.16.c)$$

$$x(4) \xrightarrow{yields} \textstyle\sum_{k=1}^{K} \mathrm{d(k, t)} \quad (4.16.d)$$

$$x(5) \xrightarrow{yields} \textstyle\sum_{k=1}^{K} \mathrm{b_k(k, t)} \quad (4.16.e)$$

$$x(6) \xrightarrow{yields} \mathrm{b_e(t)} \quad (4.16.f)$$

$$x(7) \xrightarrow{yields} \mathrm{b(t)} \quad (4.16.g)$$

$$x(8) \xrightarrow{yields} \mathrm{e(t)} \tag{4.16.h}$$

The variables $x(1)$, $x(2)$ and $x(3)$ define the total energy generated by turbine and photovoltaic panels, which is stored in the battery, injected into the electricity grid and used in consumption, respectively. The $x(4)$ variable is the total net demand in the period analysed, the $x(5)$ the total energy supplied to the consumption from the battery and the $x(6)$ the energy that is transferred from the battery to the surplus. Finally $x(7)$ is the total energy stored in the battery in the period analysed and $x(8)$ the total surplus.

Matrices

In treating the problem according to the above variables, it is only necessary to define the linear constraints and the bound variables. The matrices have been generated to define the optimization problem in the Matlab software. The ones defined in citation 4.17 and 4.18 are part of the linear constraints and 4.19 are the bound variables. In the case of matrix 4.17, it will be necessary to repeat the eight columns as many times as T periods are used in the problem (in this case one year). This matrices are come from the coefficients of equations 4.9 to 4.13 and are ordered according to the solution of the problem $\boldsymbol{x}$.

$$\boldsymbol{Aeq} = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \cdots \\ 0 & 0 & 1 & 1 & \eta & 0 & 0 & 0 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \cdots \\ -\eta & 0 & 0 & 0 & 1 & 1 & 1 & 0 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \cdots \\ 0 & 1 & 0 & 0 & 0 & \eta & 0 & -1 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \end{bmatrix} \tag{4.17}$$

$$\boldsymbol{beq} = \begin{bmatrix} G(1) \\ \vdots \\ G(T) \\ D(1) \\ \vdots \\ D(T) \\ 0 \\ \vdots \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{4.18}$$

The matrices of the bound variables will set the constraint of the battery located in Eq. 4.13.

$$\boldsymbol{LB} = \mu \cdot B \cdot \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \quad \boldsymbol{UB} = B \cdot \begin{bmatrix} \infty & \infty & \infty & \infty & \infty & \infty & 1 & \infty \\ \infty & \infty & \infty & \infty & \infty & \infty & 1 & \infty \\ \infty & \infty & \infty & \infty & \infty & \infty & 1 & \infty \\ \infty & \infty & \infty & \infty & \infty & \infty & 1 & \infty \\ \infty & \infty & \infty & \infty & \infty & \infty & 1 & \infty \\ \infty & \infty & \infty & \infty & \infty & \infty & 1 & \infty \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ \infty & \infty & \infty & \infty & \infty & \infty & 1 & \infty \end{bmatrix} \tag{4.19}$$

Minimizing function

The minimizing function has had to be developed separately because it is necessary to apply loops to solve the sums that equation 4.20 includes.

$$z = \sum_{t=1}^{T} \left(C_D(t) \cdot \sum_{k=1}^{K} d(k, t) - C_E(t) \cdot e(t) \right) \tag{4.20}$$

The program developed, what it is creating a list of values with the calculations of z per T times and at the end it gives us a sum of all these terms, which will be what has to minimize the optimization problem.

```
function f_sum = objectiveFun(x)
    global T Cd Ce z
     d = x(4);
     e = x(8);
    for i=1:T
        z(i) = Cd(i)*d(k,t)-Ce(i)*e;
    end
    f_sum = sum(z);
end
```

Chapter 5

5 Definitive Sustainable Proposal

5.1 Hybrid Solution

Considering the amount of renewable sources of energy available in Granollers area, the hybrid solution would consist in a water utilization system through a microturbine in the main pipeline connected to a photovoltaic system, which will capture solar energy. This energy would be distributed within the different consumptions, while the surplus of energy would be stored in batteries in order to be distributed to electricity network or to consumption when it cannot be generated directly.

In order to implement this solution, it has been separated within the following cases: hydraulic study of the water's network, study of companies' solar capacity, and a final optimization through Matlab.

5.1.1 Hydraulic Energy System

Main consumers of water in the area

Firstly, it is studied the consumption impact of the industrial estates Coll de la Manya and Fond del Ràdium concerning the whole city of Granollers. This information has been obtained from the water company of the area and the council of the city.

Fig. 5.1 shows the consumption ratio of the industrial companies that consume the most water in the city of Granollers. The ratio of the circumferences means the amount of cubic metres of water consumed and the colour means the proportion that comes from a well or from general consumption. The industrial areas studied are marked on the west of the map.

It can be observed that it is not an industrial estate with a high amount of water consumption. Despite that, there are some companies with significant consumption:

ID in Figure 6.1	ID in Thesis	Company	Annual Consumption [m3/year]
21	28	CRICURSA	17475
22	56	COALIMENT GRANOLLERS	21320
36	30	MONDELEZ ESPAÑA	8011

Table 5.1: *Main consumers of water of industrial areas studied.*

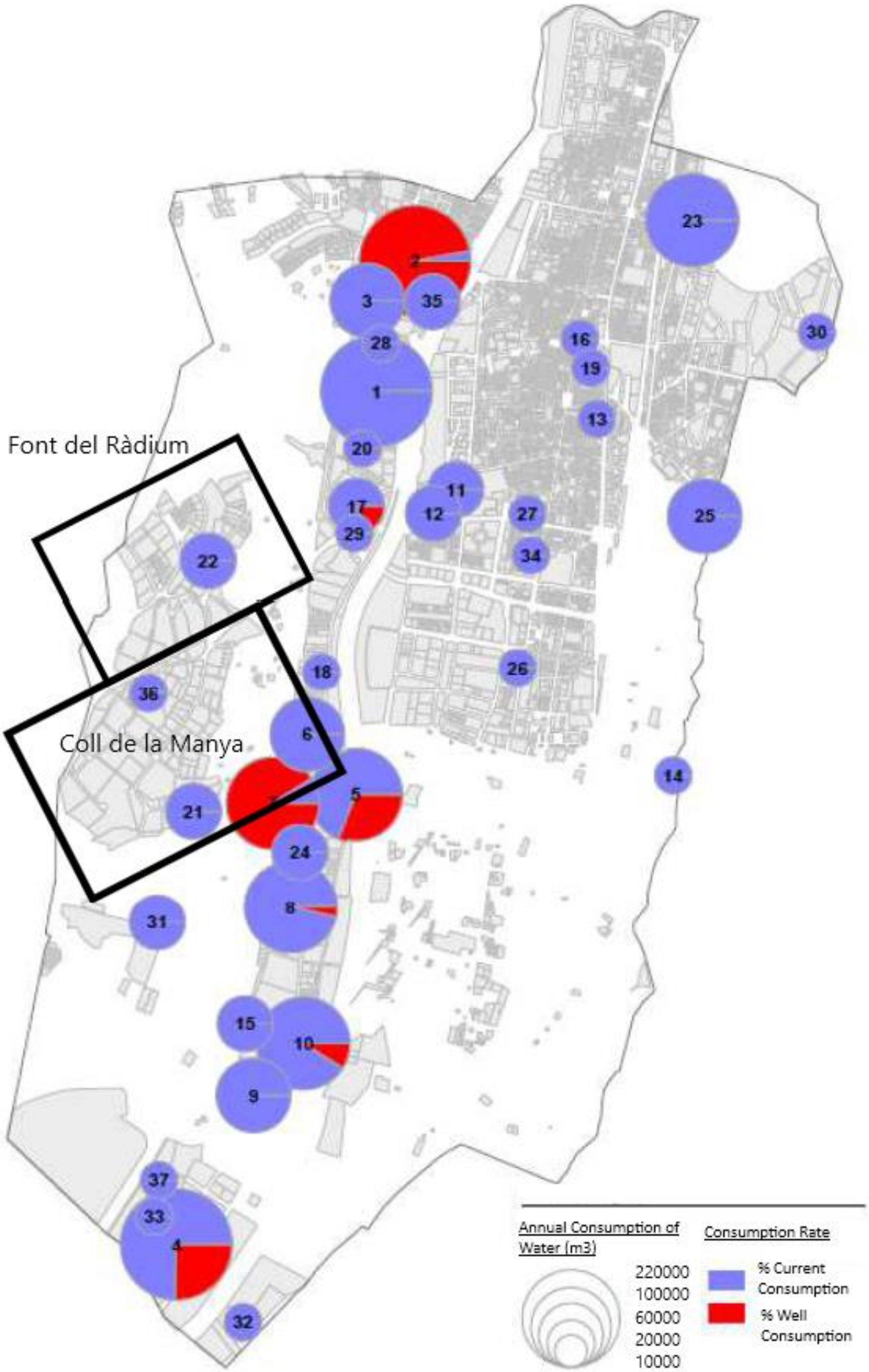


Figure 5.1: *Main consumers of water in Granollers.*

Thanks to the information obtained from the water company Sorea, we can distribute the water annual consumption per company and obtain the nodes for the study in WaterGems. This software is a hydraulic modelling application for water distribution systems with advanced interoperability, geospatial model building, optimization, and asset management tools.

The objective consists on associating the nearby companies, which could build an energy community according to the study *Clustering of Observations* performed in the statistic part and consequently, assigning the sum of the water demands of the energy community in nods or pipe networks in order to harness more hydraulic energy. Fig. 5.2 shows a map with the 50 observations (all companies clustered), divided by different potential groups to establish energy communities, and their respective yearly water consumptions.

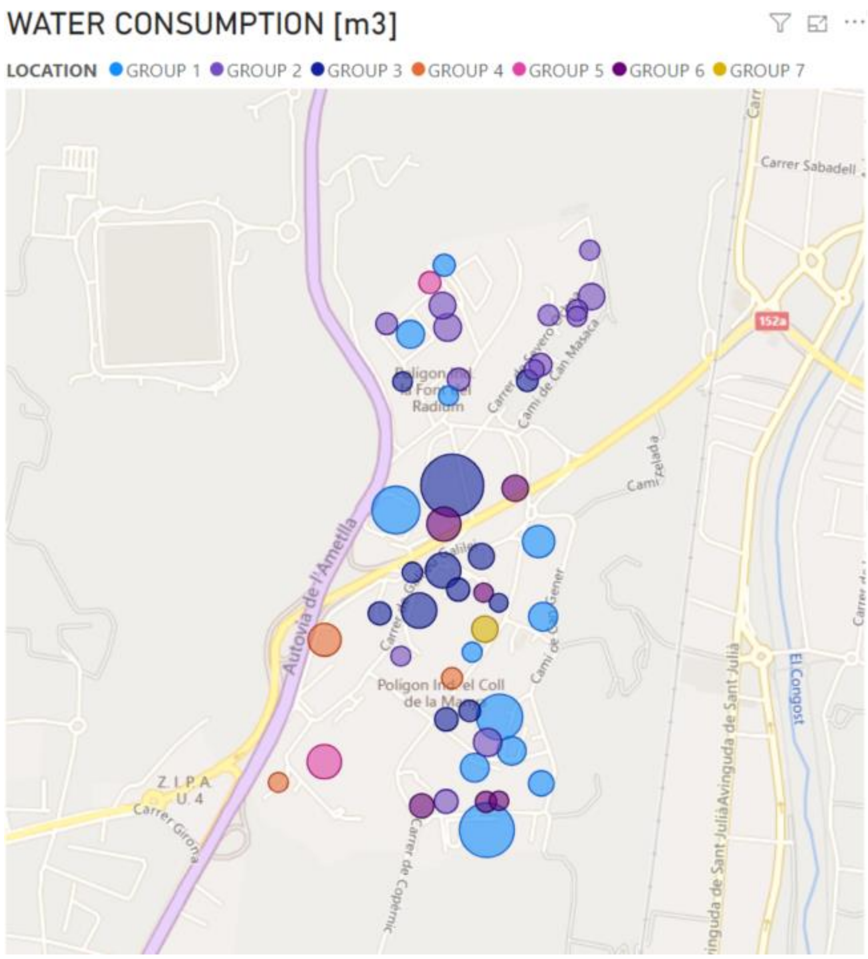


Figure 5.2: *Water consumption of companies divided by groups.*

In this way, it is easy to detect in which areas it would be feasible because the colour shows the proximity of the companies, which are from the same group, and the circumference thickness shows the amount of water consumed. In Figure 5.3, it is possible to detect a first view of which groups could have optimal points for establishing turbines due to their volume of water consumed.

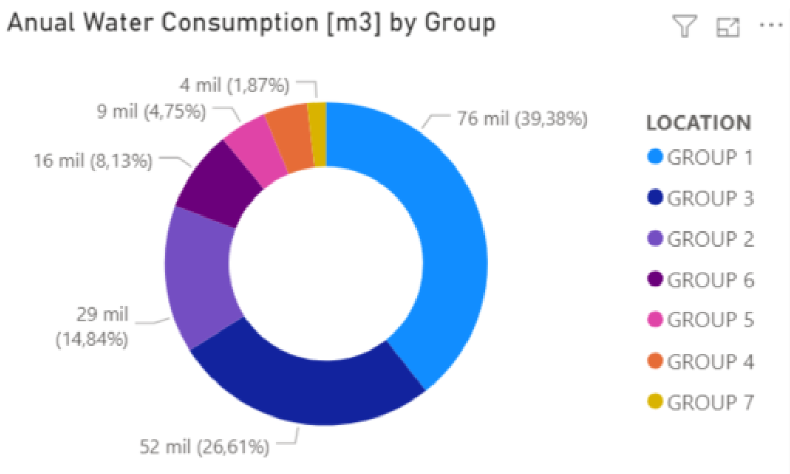


Figure 5.3: *Annual water consumption by groups established in chapter Sharing groups.*

It is important to highlight that Group 3, which has been chosen to develop the project in the section 4.2, it is an optimal candidate considering the year water consumption because it accounts for the 26,61% approximately of the entire Industrial Park. Moreover, Group 1 and Group 2 could be next candidates to be studied with the main of implementing an energy solution to a large number of companies of the Industrial Park.

Hydraulic model to implement

This model consists on analysing each case of community energy separately and implementing a model with microturbines in the main water pipe of consumer companies, taking advantage of the energy obtained from the Pumping Head from the main tank to the turbine.

$$P_H = \rho \cdot g \cdot H \cdot Q \cdot \eta_{turb} \tag{5.1}$$

Where H is the waterfall from the main tank (m), Q the total amount of companies (m^3/s), η_{turb} the performance of the installed turbine and ρ the water density (1000 kg/m^3).

The micro-turbine will convert the hydraulic energy into mechanical energy, that afterwards will be converted into electric through a generator connected to the micro-turbine. The micro-turbine will then distribute part of the energy generated to the electricity grid, another part to the load (end consumers) and finally through an AC/DC converter to store it in batteries.

The total electric power generated can be calculated from the following theoretical formula Eq. 5.2, which depends on the electromechanical efficiency of the turbine. The turbine efficiency is considered from data sheets of manufacturer.

$$\eta_{em} = \frac{P_{ELECT}}{P_H} = \frac{P_{ELECT}}{\rho \cdot g \cdot H \cdot Q \cdot \eta_{turb}} \tag{5.2}$$

Fig. 5.4 shows the scheme of the optimization model applied if only the micro-turbine will be used. It can be seen how the use of the water consumed allows the turbine to generate energy that is distributed to consumption, the battery and the electricity network. The orange line can also be seen, which is the energy provided by the electric company. The inverter should be placed between the turbine and the power grid (green line).

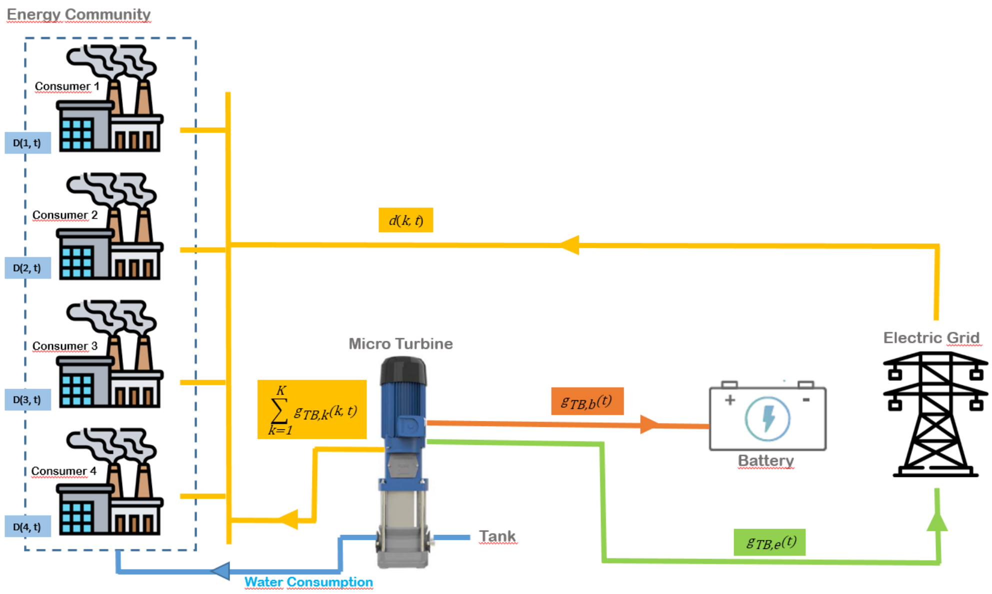


Figure 5.4: *Micro-turbine diagram in a grid-connected installation.*

Therefore, in the theoretical model what is studied is done through a generic turbine with a nominal power defined in the following sections and then extrapolated in each case according to the flow and the height of the available pressure.

Study of the Hydraulic Map in WaterGems

It has been simulated the hydraulic map of the area of the Industrial Park with the Software WaterGerms and AutoCad. Moreover, it has been placed in every node its height and water demand in l/s according to the nearby companies, information provided by Granollers Council and the water company SOREA. All nodes, pipes and elements can be seen in Fig. 5.6.

In Fig. 5.5, we can see how each node has its own characteristics such as the label, the elevation or the demand that must be introduced in the program.

	ID	Label	Elevation (m)	Zone	Demand Collection	Demand (L/s)	Hydraulic Grade (m)	Pressure (m H2O)
39: J-6	39	J-6	145,50	<None>	<Collection: 1 item>	0,00	177,42	32
42: J-8	42	J-8	136,50	<None>	<Collection: 1 item>	0,00	177,56	41
45: J-10	45	J-10	162,00	<None>	<Collection: 1 item>	0,22	177,38	15
48: J-12	48	J-12	161,70	<None>	<Collection: 1 item>	0,00	177,37	16
50: J-13	50	J-13	170,80	<None>	<Collection: 1 item>	0,11	177,41	7
54: J-16	54	J-16	148,50	<None>	<Collection: 1 item>	0,00	177,38	29
57: J-17	57	J-17	139,00	<None>	<Collection: 1 item>	0,02	177,57	38
60: J-19	60	J-19	153,50	<None>	<Collection: 1 item>	0,00	175,66	22
63: J-21	63	J-21	147,70	<None>	<Collection: 1 item>	0,68	177,38	30
66: J-23	66	J-23	126,50	<None>	<Collection: 1 item>	0,00	177,56	51
69: J-25	69	J-25	158,30	<None>	<Collection: 1 item>	0,02	177,37	19
73: J-28	73	J-28	162,00	<None>	<Collection: 1 item>	0,03	177,38	15
77: J-30	77	J-30	150,30	<None>	<Collection: 1 item>	0,00	177,37	27

Figure 5.5: *Defined table in Watergems of the hydraulic map nodes (J).*

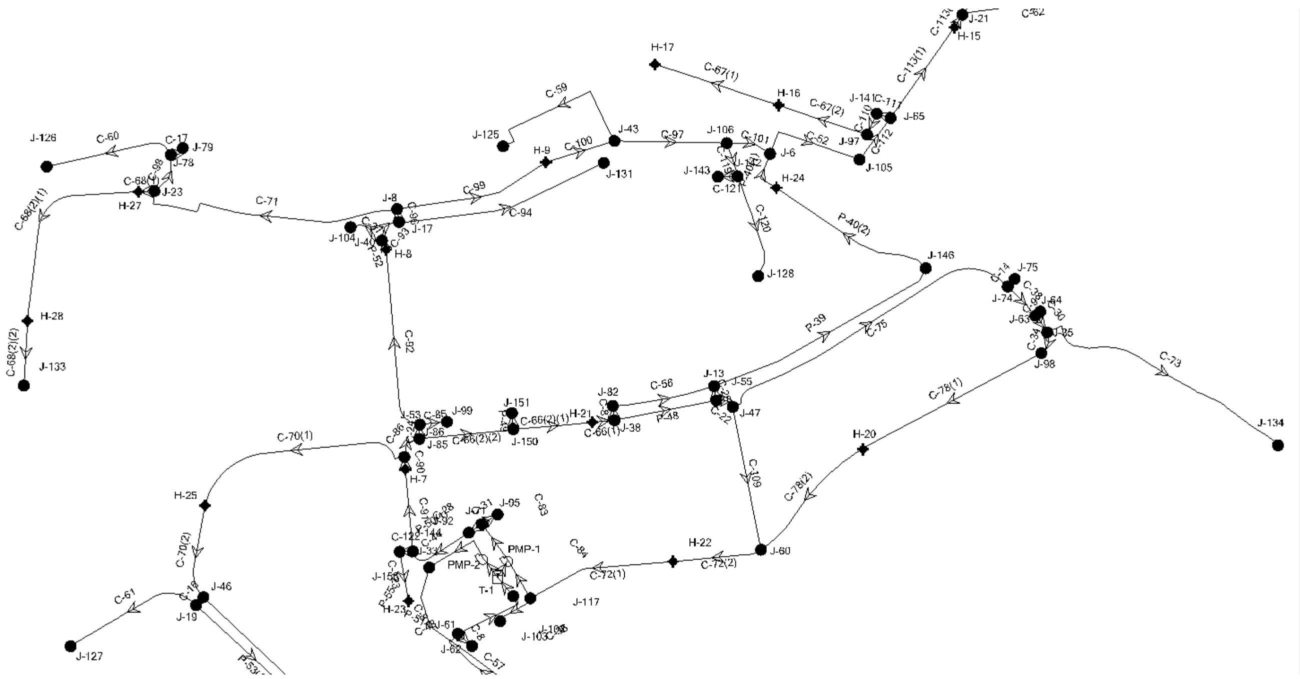


Figure 5.6: Most important points of hydraulic map analyzed in the software Watergems.

Besides that, it has been inserted the characteristics of the pipes between nodes, such as material, diameter and length. It is shown in Fig. F.3, concretely, in the Annex F.

It is important to define the main tank from where it drains all the area consumptions, as well as, the pumps, which drive the water so that it reaches all the nearby nodes analysed in this study. Figure 5.7 shows tank parameters such as base elevation, maximum elevation, initial elevation and diameter.

	ID	Label	Zone	Elevation (Base) (m)	Elevation (Minimum) (m)	Elevation (Initial) (m)	Elevation (Maximum) (m)	Volume (Inactive) (ML)	Diameter (m)	Flow (Out net) (L/s)	Hydraulic Grade (m)
319: T-1	319	T-1	<None>	170,00	170,00	174,00	176,37	0,00	20,00	6,74	174,00

Figure 5.7: Defined row in Watergems of water tank..

It is also necessary to define the direction of the pumps located around the tank as well as the water pumping and drainage pipes, which usually come from a lower lifting point. Properly introducing the outcome of the tank for the distribution of the water for every conduct of the main consumptions of the area it is a key point for the proper function of the model. As follows, it is illustrated in Fig. 5.8 how it has been made the connection of the main pipes in WaterGerms software:

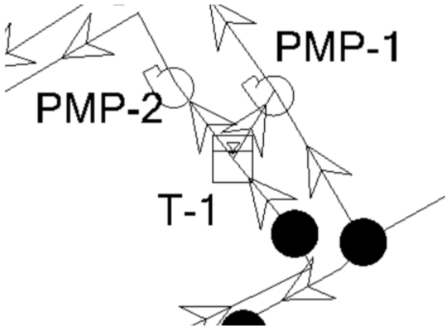


Figure 5.8: *Tank and pumps diagram for the entrance and exit of water.*

The nomenclature of the pumps and the tank is as follows:

PMP-1: Distribution pump to the companies’ consumption.

PMP-2: Water source rise pump for tank filling.

T-1 : Main deposit of the installation.

	ID	Label	Elevation (m)	Pump Definition	Status (Initial)	Hydraulic Grade (Suction) (m)	Hydraulic Grade (Discharge) (m)	Flow (Total) (L/s)	Pump Head (m)
321: PMP-1	321	PMP-1	170,20	Grundfoss CR30	On	174,00	175,16	11,99	1,16
469: PMP-2	469	PMP-2	170,20	Grundfoss CR30	On	174,00	217,72	0,14	43,72

Figure 5.9: *Defined table of pumps in Watergems.*

Based on the above features in Fig. 5.9 and once the pump curves, shown in Fig. 5.13, have been obtained, a simulation of the entire hydraulic map is carried out where the hydraulic pressure and flow of all nodes in the installation are obtained. From this point on, it is decided which points will be candidates to form an energy community being viable for the use of micro-turbines in their hydraulic networks. These points will be the ones that have the highest possible flow and a pressure above 25 mWc.

A summary of the global results generated in Watergems is shown in Appendix F.3, together with a map of the most interesting points for the placement of micro-turbines in the water distribution network.

The results have been filtered according to those pipes with a flow rate of more than 2.5 L/s. This value is used because there are enough points to place the turbine in front of it and also the lower the water flow the more difficult it is to find a turbine.

The candidate nodes are located in tables of Appendix F.3 and the others have been discarded according to the restriction of a minimum of 25 mWc of hydraulic pressure at the consumption inlet, established by the source [16]. If this value were to be reduced, it could cause problems in the companies' supply, not ensuring the pressure of the taps.

The nodes and the pipes of Appendix F.3 are now available to establish a first map of the optimal points to place a micro-turbine. In Figure 5.10, there are in colour red, the areas that would be evaluated for the possible incorporation of hydraulic system.

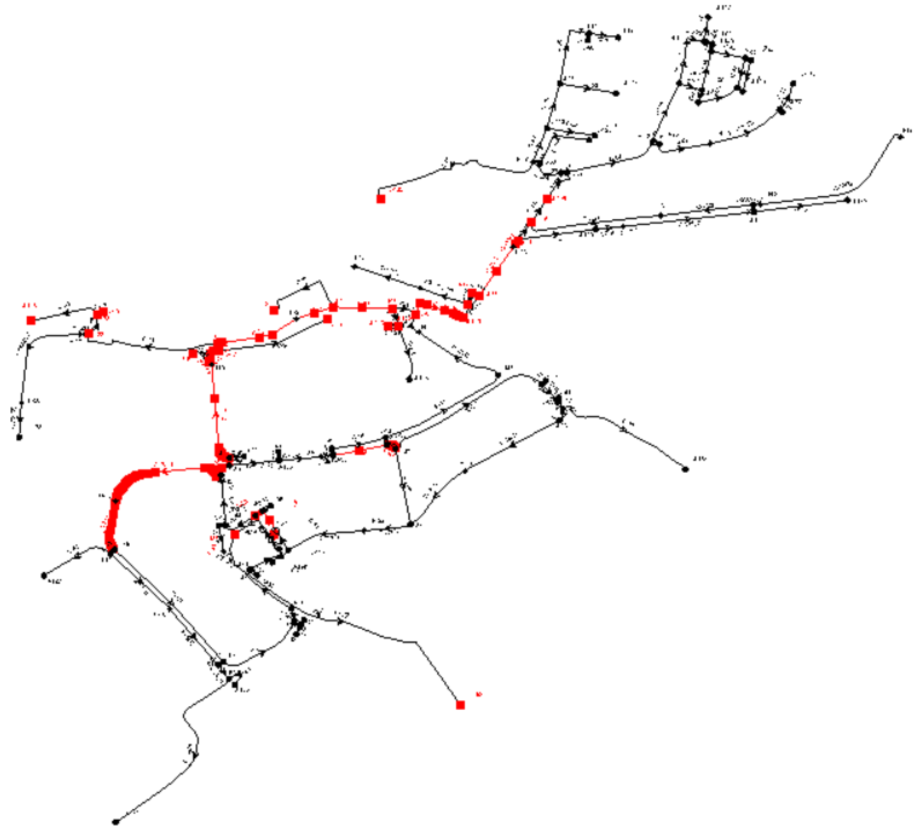


Figure 5.10: *Area where the micro-turbine will be placed.*

It is important to evaluate those pipes of Appendix F.3 and Fig. 5.10, which are in contact with a candidate node and vice versa. Otherwise, we would probably not fulfil the minimum restrictions.

Once the model has been analysed and the most optimal locations have been found (energy study), i.e. with the highest power produced, the micro-turbine will be selected according to the flow and pressure height in the technical sheets of the models mentioned in the next section Turbine Selection. From there, these elements will be inserted in the model and it will be obtained the hydraulic power that the system is capable of generating for a particular case (small group of companies).

Hypotheses developed in WaterGems

The main tank is defined as the one that supplies the water to all the nodes. It has a capacity of 2000 m^3, that is, a height of 6.37 meters and a diameter of 20 meters. Its base is located at an elevation of 170 meters above sea level (one of the highest points in the industrial area) and therefore has a maximum elevation of 176.37 meters. It is considered as an initial hypothesis that it is 63% full (174 meters of elevation). This value is the average value of water volume in which the tank is during all the days of the year and has been provided by the water company of the area (SOREA).

All the nodes located in the hydraulic map in which it is considered that there is no nearby company that can provide a water consumption, will be named non-consumption nodes. These will be set to a constant demand (that tends to zero but not negligible) because the model works properly and water flows through them.

In the study, two scenarios or hypotheses have been made to see the data's volatility according to the number of companies studied. It is known that there are 153 companies on the industrial area, of which only 50 candidates have been specifically studied to enter the project.

The first hypothesis is to include only the 50 companies and their demands, while the second includes the 153.

- Scenario 1 (50 companies): the sum of all the consumption of the 50 companies, i.e. 6.21 L/s (195986 m^3/year), will be set as the demand for the tank. All non-consumption nodes will have a constant demand of 0.001 L/s.

- Scenario 2 (153 companies): In this case, the demand of the tank will be set at 10.03 L/s, i.e. 316280 m^3/year. The non-consumption nodes will be set at an average of the remaining consumption (120294 m^3/year) according to the consumption of the 103 enterprises not accounted in the previous scenario, i.e., dividing the remaining consumption among the 103 companies will be 0,037 L/s for node.

To simplify the study slightly, an equal hourly demand pattern has been inserted in the Fig. 5.11**,** for all companies where the hours with maximum consumption are between 9 am and 7 pm. The minimum hours are grouped together from 23 pm to 5 am, which is when the companies are normally not active. For non-consumption nodes, a constant pattern has been established.

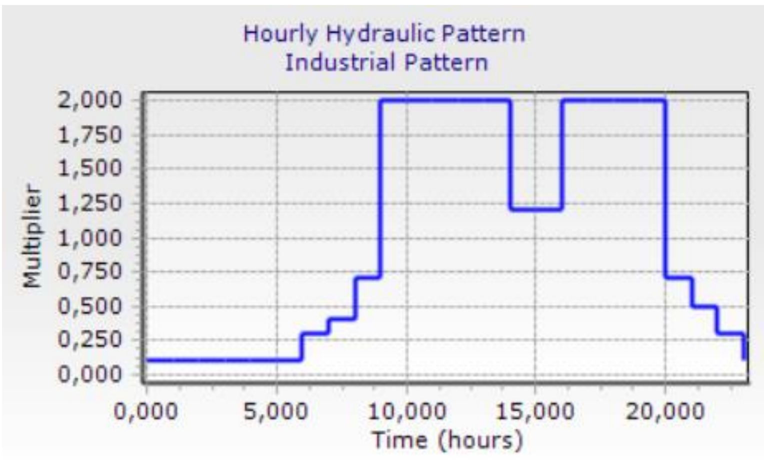


Figure 5.11: *Hourly demand pattern for water consumption of industrial building.*

The pipes are all made of 5 different materials; Cement Asbestos, Ductile iron, Polyethylene, PVC and Galvanized iron. Each one has its own properties defined in the WaterGems library. The diameters vary in the hydraulic map between 25 and 350 mm, being the 100 and 150 mm the most common.

An absolute roughness of 0.1 mm is considered according to Darcy-Weisbach's criteria and the length of the pipes is over-dimensioned by 15% to take into account the unique conduction losses.

The elevation of each node is fixed thanks to a cartographic map of the area provided by Granollers City Council and where it has been extrapolated to those points that were in the middle of two regions.

The system has two pumps installed in the tank: one that helps to fill the tank from the river to the flattest areas of the city (rising pump) and another that distributes to the pipes of the industrial areas to feed the consumption of the companies (distribution pump). The characteristics have been obtained from Fig. 5.12 and shown in Table 5.2, through a visit to the installation and it has been determined that both are of the **Grundfoss** brand and model **CR30-30 A-F-K-BBUV**.

Figure 5.12: *Pump plate with its technical features.*

GRUNDFOSS CR30-30 A-F-K-BBUV	
n : Nominal speed (rpm)	2900
Q : Nominal flow (m^3/h)	30
H : Nominal Head (m)	30.5
P : Power (kW)	4
Liquid type / Working temperature (°C)	Water / 20
Maximum pressure (bar) / Temperature (°C)	16 / 120

Table 5.2: *Features of pumps installed in the zone.*

The performance curves according to manufacturer are as follows:

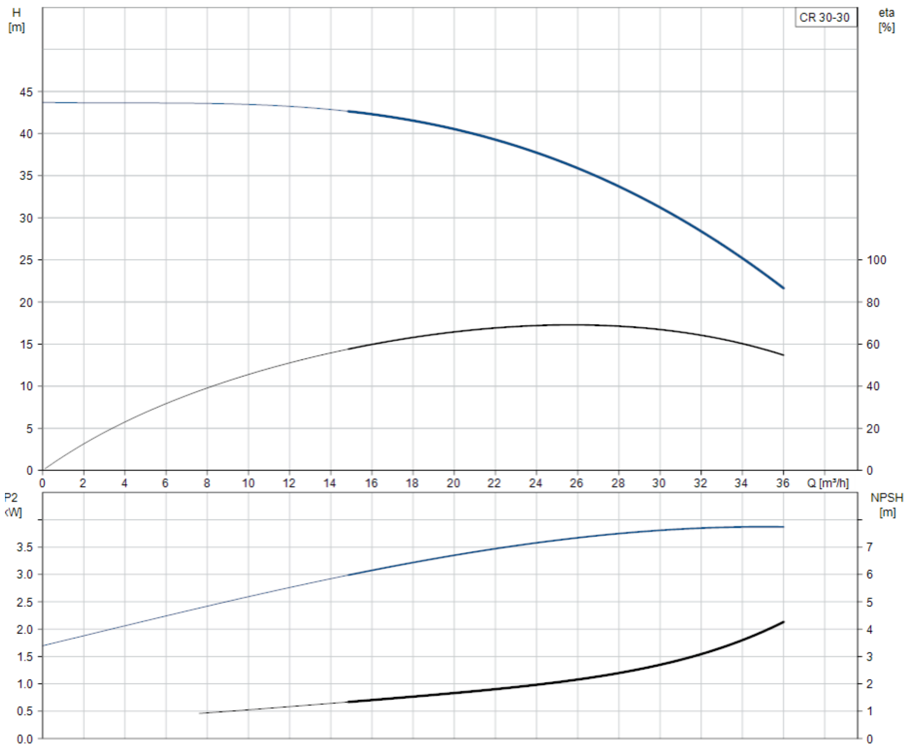


***Figure 5.13:** Curves H-P-Q-η of pumps installed.*

In Figure 5.13, the four curves are related to the flow rate (Q) of the pump. In the graph above, the curve is shown in blue, which would be the correlation with the pressure drop (H), and on the other side, the black curve, with the efficiency of the pump. In the second graph, the power curve is shown in blue and the NPSH coefficient in black.

For the main study of the hydraulic map, the following hypotheses have been considered in the WaterGems software:

1- **Head – Flow curve**: defined by random 3 points table.

	Flow (L/s)	Head (m)
Shut off	0	43.72
Design	4.36	42.56
Max. Operating	9.81	22.90

2- **Efficiency – Flow curve**: defined by multiple points.

	Flow (L/s)	Efficiency (%)
1	0.58	12.9
2	2.11	37.8
3	4.31	58.9
4	4.46	60
5	4.68	61.4
6	5.01	63.2
7	8.39	66.7
8	9.63	58.5
9	9.68	58.1
10	9.94	55.4

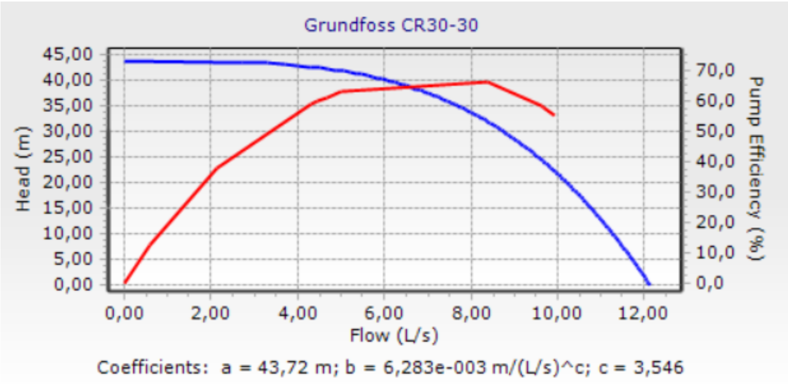


Figure 5.14: *Equations of pumps inserted in software Watergems.*

3- **Inertia** defined as Pump plus Motor: 998.2 kg·m^2.

4- **Speed** and **Specific Speed** in nominal conditions: 2900 rpm / 3300 rpm

5- **Elevation** in the map: 170.2 m above sea level.

6- Water **Liquid** consideration at 20 ºC during operation.

Results applied to the particular case (Group 3)

In this section, we will analyse the hydraulic results obtained before to the particular case with the 4 companies chosen (ID14, ID20, ID31, ID33). In order to obtain the hydraulic energy obtained from the consumption of these companies, it will be necessary to evaluate the closest optimal points. For this purpose, a new scenario has been created in the program called Zone 1 that includes all these nodes and pipes. This Zone 1 is shown in colour red in the Fig. 5.15.

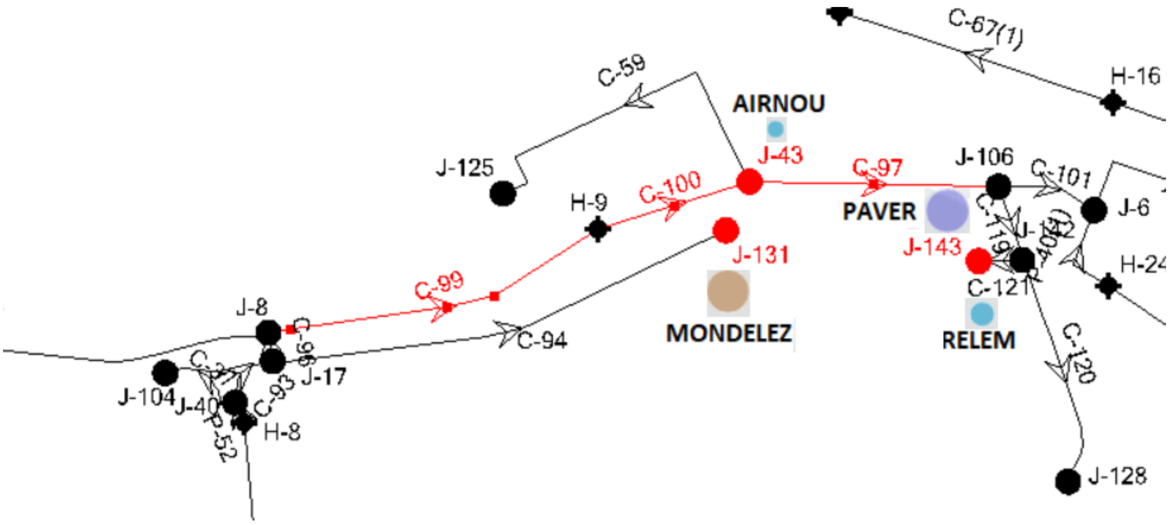


Figure 5.15: *Final zone where probably micro-turbine will be installed.*

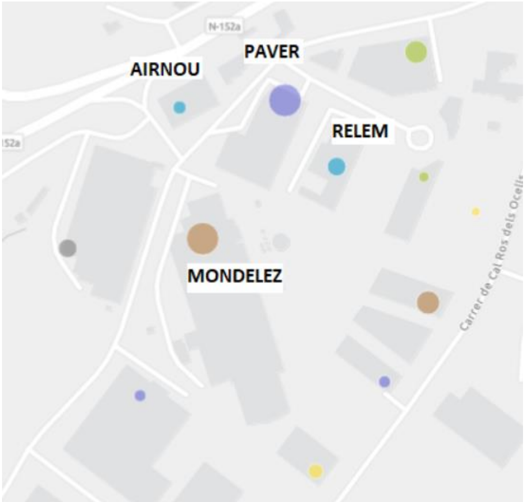


Figure 5.16: *Location of the final candidates.*

Group 1 companies are located as follows on the hydraulic map:

ID 30 – MONDELEZ INTERNATIONAL S.A. → **J-131 /** ID 39 – RELEM → **J-143 /**
ID 62 – AIRNOU S.L. → **J-43 /** ID 65 – PAVER → **J-143**

ID 65 and ID 39 share the same consumption node due to their proximity, so they are located at a similar elevation. The hydraulic pressure results in these nodes without incorporating a turbine are as follows:

ID Junction	Pressure (mWc)
J-131	31
J-143	30
J-43	33

Table 5.3: *Pressure of the final nodes in their supply area.*

Concerning the results of flow and speed in the pipes, they have been compared in the two scenarios commented (50 consumer companies versus 153 companies) and it is observed that there is not much variability. This is reflected in the fact that in the first scenario the companies with the highest water consumption in the industrial area were used and, although they are fewer, they consume 62% of the total.

ID PIPE	SCENARIO 1 (50 COMPANIES)		SCENARIO 2 (153 COMPANIES)	
	Flow Q (L/s)	Velocity v (m/s)	Flow Q (L/s)	Velocity v (m/s)
C-97	2,60	0,15	2,70	0,15
C-99	2,94	0,17	3,03	0,17
C-100	2,91	0,16	3,02	0,17

Table 5.4: *Comparison of Watergems scenario results*

According to the results obtained in Tables 5.3 and 5.4, it is obvious that the optimum location is the one where the most capacity and speed is generated, because in the three pipes studied the diameter is constant (150 mm) and the hydraulic pressure is very similar. Therefore, it is concluded that the micro-turbine for this group of companies will be placed at the end of the **C-99** pipe, more specifically at the node containing an **H-9** hydrant with a hydraulic pressure of 31 m H_2O.

Turbine Selection

In this case, the Spanish brand Tecnoturbines has been selected because it is a good manufacturer and it allows a comfortable assembly and maintenance in the industrial area of Granollers. The first step was a study of all the turbines available, according to the flow rate and hydraulic pressure required, and dividing them into those that can be used for an autonomous system or connected to the network.

In the following tables, the colour red has been used to determine the requirements that are not suitable for the previous conditions and the colour green for the optimum ones.

a) <u>Standalone system</u>

MODEL	Pressure (mWc)		Flow (L/s)		Power (W)	SELECTED
Turbine HE (Inline HP)	5 - 300		1 - 8		100 - 3000	
Turbine HE (Inline)	5 – 40		4 – 20		100 - 3000	
Picoturbina	1 - 25		0,5 - 1		0 - 25	

Table 5.5: *Features of different types of turbines for autonomous systems.*

The pressure and flow rate defined in the previous section have been compared to coincide with the ranges provided by the turbines data sheets in Table 5.5. Once the majority of models are rejected, the power of the turbine HE (Inline HP) must be set to obtain the hydraulic energy.

The Figure 5.17 is obtained from the following manufacturer's curves (Pressure drop - Flow) and it will help us to obtain the power of the turbine. By setting the flow rate and pressure, we will obtain in which curve our turbine will work.

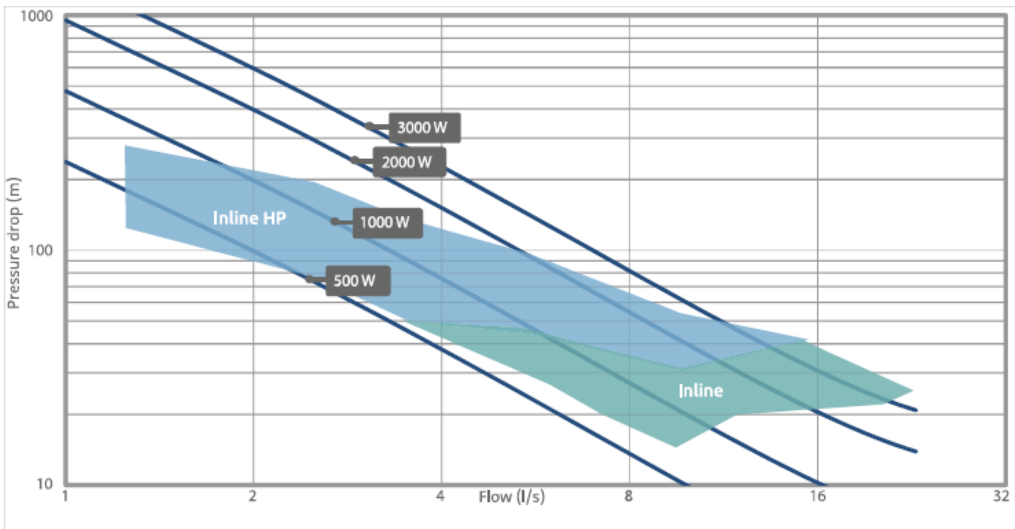


Figure 5.17: *Curves of Turbine HE, Tecnoturbines brand.*

b) <u>Connected to grid system</u>

MODEL	Pressure (m H2O)		Flow (L/s)		Power (kW)	SELECTED
Micro Regen System (Inline HP)	25 - 400		1 - 45		2 – 25	
Micro Regen System (Inline)	10 – 198		8 – 150		2 – 25	
Hydro Regen System (Inline HP)	25 - 400		1 - 45		0 - 25	
Hydro Regen System (Inline R)	10 - 135		105 - 500		25 - 900	
Hydro Regen System (Inline)	10 – 198		8 – 150		2 – 25	

Table 5.6: *Features of different types of turbines for connected to grid system.*

The pressure and flow rate defined in the previous section have been compared to coincide with the ranges provided by the turbines data sheets in Table 5.6**.** In this case, two types of turbines can be chosen for the case of a grid-connected system. In order to decide which one to use, it is necessary to differentiate the type of system (Micro or Hydro) using the Fig. 5.18:

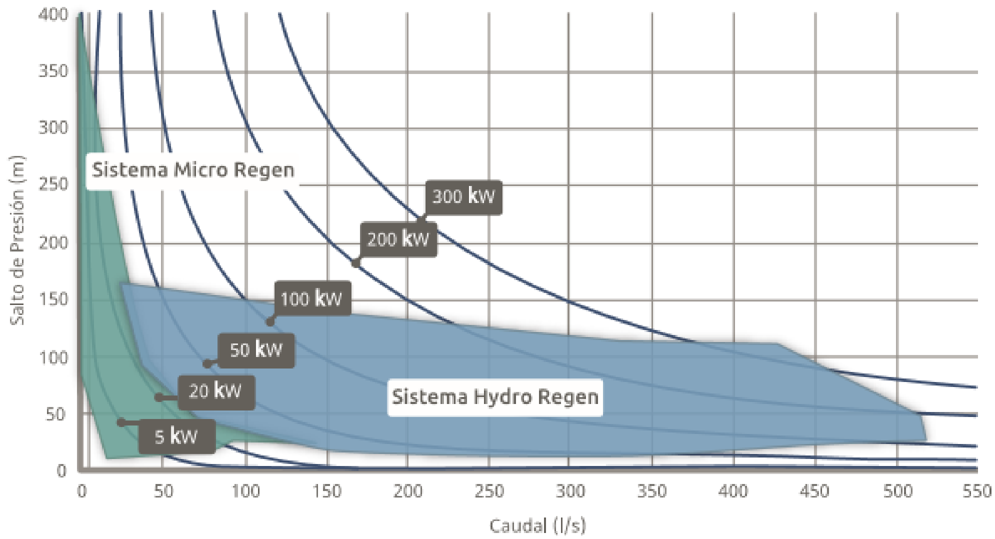


Figure 5.18: *Curves of Micro Regen or Hydro Regen system, Tecnoturbines brand.*

It should be noted that for the conditions of the C-99 pipe specified in Tables 5.3 and 5.4, a micro-turbine of the **Micro Regen** system is required, which according to the technical specifications provided by Tecnoturbines requires an IE4 efficiency generator (93-94%).

For a hydraulic flow of 3.03 L/s and a pressure drop of 6 mWc (difference between point pressure and minimum pressure to supply) in the C-99 pipe, a **0.178 kW** turbine is chosen for the grid-connected model and stand-alone system. The pressure drop is given by the difference between the pressure drop from the tank to the pipeline (31 mWc) and the minimum required consumption pressure (25 mWc). It can be observed clearly that with the same flow, we will be able to generate more energy using the turbine for connected systems to the network that they use the surplus to sell it to the electric company or to the neighbouring companies.

Thus, the micro-turbine to be used will be of the Micro Regen type from the Tecnoturbines company, which is optimal for recovering energy from points with excess pressure. These allow the recovery of surplus energy that does not exceed 25 kW of usable electrical power (maximum power obtained from technical specifications of Tecnoturbines Company). Furthermore, they can be installed directly on existing pipes in any manhole, tank inlet or consumption point as in the case shown in Fig. 5.19.

For the model connected to the grid, they have an IE4 certificate, i.e. with a generator efficiency according to rated values between 93 and 94%, while the stand-alone model has the lower certificate, IE3, but also with a good efficiency (85-90%).

The overall efficiency is calculated by multiplying the efficiency of the generator by the efficiency of the turbine. In the case of the one used for autonomous systems, it has an efficiency of 33% and the one connected to the network has an efficiency of 46%.

Figure 5.19: *Micro-turbine connected to the electric grid with Micro Regen system.*

These turbines include a permanent magnet generator and a regenerative electronic control board that maximizes the energy output of the turbine and injects the generated electric power into the grid. It is completely adapted to the diameters of the adopted solution and it works between 25 and 350 mm depending on the model. For the transmission of the energy to the batteries and directly to the consumption, it will be necessary to connect the electric power generator to an inverter system.

5.1.2 Photovoltaic Energy System

Photovoltaic panels

It has been decided that the photovoltaic modules of the brand SHARP and model ND-R250A5 will be installed. Their dimensions are 1652x994x46 mm and each one weighs 19 kg, they can be placed in parallel and serial frames.

Their high performance is due to the triple collector bar technology and polycrystalline silicon cells (156.5 mm^2) with a yield coefficient of 15.2%. Furthermore, they have an anti-reflective coating to increase light absorption and obtain better energy absorption, even at low radiation.

These have a peak power of 250 W with a tolerance of 0 to +5%, which means that they will only deliver modules with power equal or greater than the specified nominal power. It is characterized by the fact that it carries 60 polycrystalline cells in series of 156.5 x 156.5 mm each, protected by a white tempered glass of 3 mm.

The product is guaranteed for 10 years and the linear performance is guaranteed for 25 years. Below is a table with some of its most important and useful features:

Important Features	Value
Peak Power (W)	250
Open circuit voltage. Voc (V)	37,6
Short circuit current. Isc (A)	8,68
Maximum power point voltage. Vmpp (V)	30,9
Maximum power point current. Impp (A)	8,10
Efficiency (%)	15,2

Table 5.7: *Main features of PV panels used.*

All the photovoltaic panels installed in every area of the polygon will be placed at an inclination of 41° (latitude of the area), independently of the type of roof. Furthermore, they will be oriented to the south position (azimuth = 0°) whenever possible, in order to take advantage of the maximum sunshine hours.

To determine the optimization variable that will give us the panels to be installed in a project, it is determined by the following equation:

$$N_{PV} = \frac{L_{md}}{HSP \cdot P_{PV} \cdot (1 - \eta_{PV})} \tag{5.3}$$

Equation 5.3 comes from source [19] (**Ventura, 2017**), and depends on the irradiation of the area, the inclination of the panel, the features of the panel (temperature, power and efficiency) and the energy demand required in the installation. Where L_{md} is the average daily consumption in W·h, HSP the area's peak solar time and P_{PV}, η_{PV}, the power and efficiency of the panel, respectively.

Solar capacity

To evaluate the solar capacity of the selected companies, a photovoltaic solar viewer is available, provided by the Granollers City Council (**ICGC Sostenibilitat**[9]). It allows to evaluate the roofs of the companies by using information such as inclination, orientation and thermal map of the irradiation in the area. In

[9] https://visors.icgc.cat/sostenibilitat/#/visor

addition, this viewer allows to obtain the annual energy generation shown in the tables below and a first elevation view with the placement of the solar panels.

In this way, it is easy to discard those roofs that are not optimal for the placement of photovoltaic panels. The following constraints have been taken as criteria for selecting roofs with solar potential:

a) Flat roofs or those with a tilt of less than 10°.

b) Roofs with a tilt greater than 10° and oriented towards azimuth 0º (with a tolerance of ± 30°).

In this way, we can evaluate company's roofs:

1) <u>ID14 - MONDELEZ INTERNATIONAL S.A.:</u>

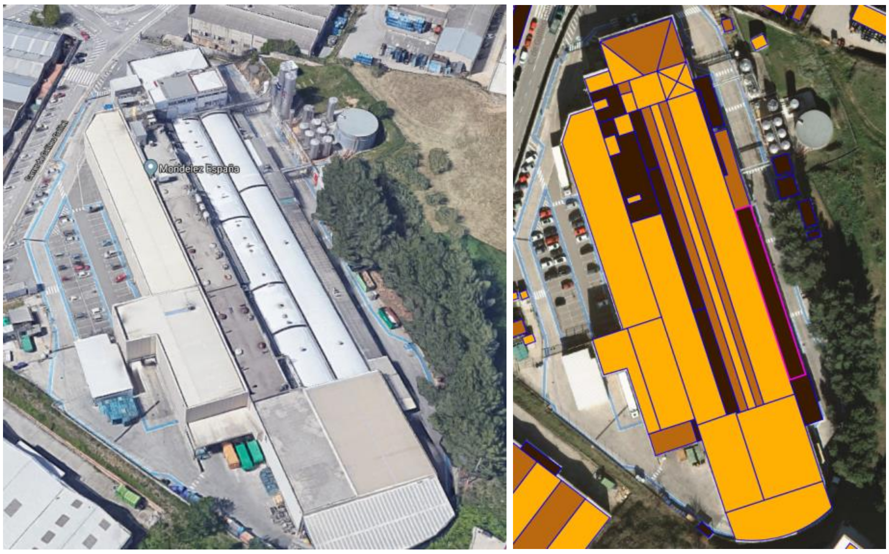


Figure 5.20: *Total roofs to evaluate the solar capacity of the company ID14.*

Figure 5.20 shows all the available roofs of the company ID14. In this case, only those areas that meet the requirements explained at the beginning can be used.

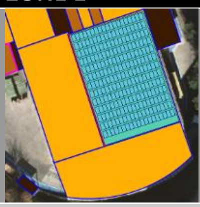
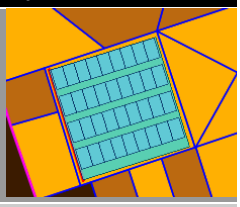
	ZONE 1	ZONE 2	ZONE 3	ZONE 4
				
Total Area	531 m^2	355 m^2	393 m^2	88 m^2
Number Panels	270	192	209	45
Panels Orientation	341°	341°	341°	342°
Roof Inclination	0°	0°	0°	0°
Useful Area	442,83 m^2	314,9 m^2	342,78 m^2	73,8 m^2
Annual Generated Energy	32065,86 kW·h	22777,29 kW·h	24202,24 kW·h	5989,81 kW·h

Table 5.8: *Useful roofs for the placement of panels for the Company ID14.*

The areas available for the installation of photovoltaic panels are defined in Table 5.8, with their maximum solar capacity in terms of useful area, number of panels and annual energy generated. If all the company's resources were used, it would have a solar capacity of 85035.2 kW·h/year, with the possibility of installing 716 photovoltaic panels in a useful area of 1174.31 m^2, which represents 16.76% of its total surface area. The maximum peak power to be installed could be 179 kWp.

2) ID33 - PAVER S.L.:

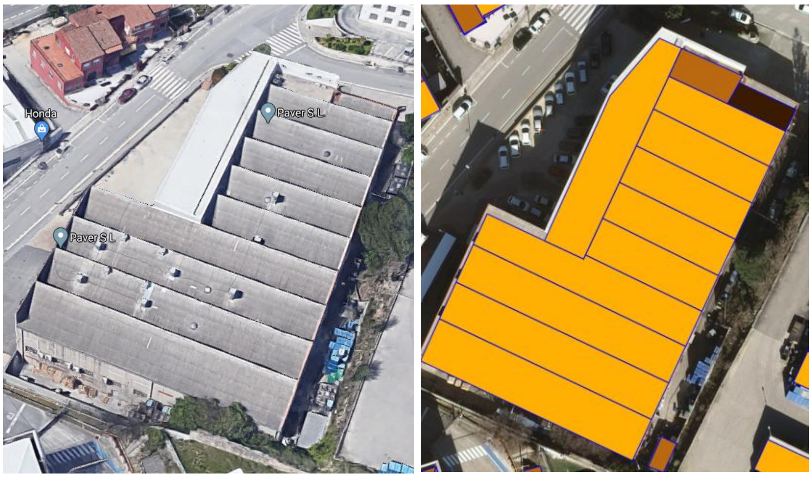


Figure 5.21: *Total roofs to evaluate the solar capacity of the company ID33.*

Figure 5.21 shows all the available roofs of the company ID33. In this case, only those areas that meet the requirements explained at the beginning can be used.

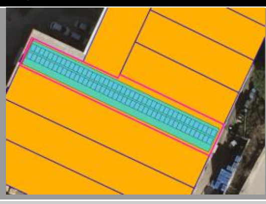
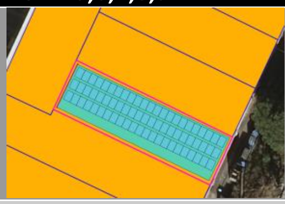
	ZONE 1,2,3	ZONE 4	ZONE 5,6,7,8,9
			
Total Area	325 m^2	234 m^2	155 m^2
Number Panels	129	86	69
Panels Orientation	24°	25°	25°
Roof Inclination	28°	25°	28°
Useful Area	211,57 m^2	141,05 m^2	113,17 m^2
Annual Generated Energy	24860,77 kW·h	17354,21 kW·h	12045,21 kW·h

Table 5.9: *Useful roofs for the placement of panels for the Company ID33.*

The areas available for the installation of photovoltaic panels are defined in Table 5.9, with their maximum solar capacity in terms of useful area, number of panels and annual energy generated. If all the company's resources were used, it would have a solar capacity of 152162.6 kW·h/year, with the possibility of 818 photovoltaic panels installed in a useful area of 1341.61 m^2, which represents 24.71% of its total surface area. The maximum peak power to be installed could be 204.5 kWp.

3) ID20 – RELEM:

Figure 5.22: *Total roofs to evaluate the solar capacity of the company ID20.*

Figure 5.22 shows all the available roofs of the company ID20. In this case, only those areas that meet the requirements explained at the beginning can be used.

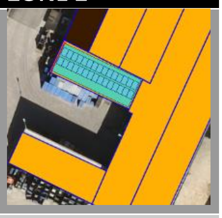
	ZONE 1	**ZONE 2**
		
Total Area	90 m^2	83 m^2
Number Panels	32	30
Panels Orientation	25°	25°
Roof Inclination	18°	23°
Useful Area	52,48 m^2	49,20 m^2
Annual Generated Energy	5831,17 kW·h	5867,96 kW·h

Table 5.10: *Useful roofs for the placement of panels for the Company ID20.*

The areas available for the installation of photovoltaic panels are defined in Table 5.10, with their maximum solar capacity in terms of useful area, number of panels and annual energy generated. If all the company's resources were used, it would have a solar capacity of 11699.13 kW·h/year, with the possibility of 62 photovoltaic panels installed in a useful area of 101.68 m^2, which represents 5.95% of its total surface area. The maximum peak power to be installed could be 15.5 kWp.

4) ID31 - AIRNOU S.L.:

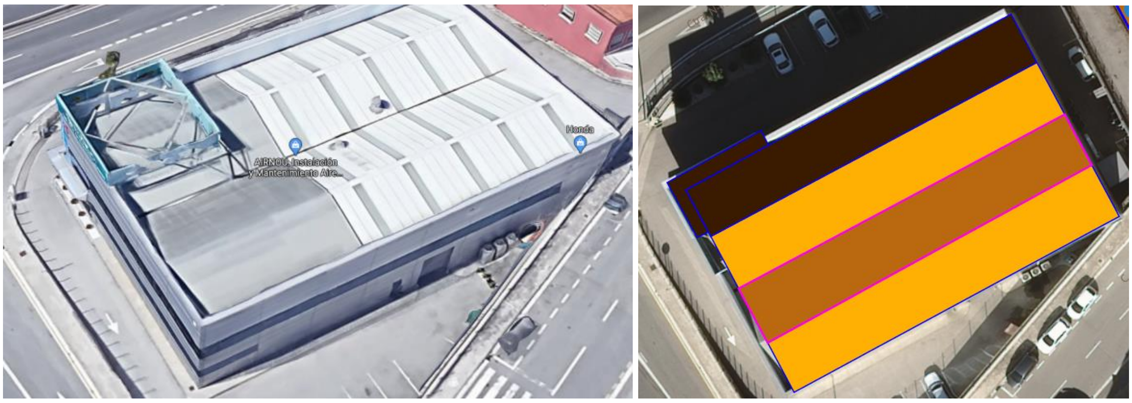


Figure 5.23: *Total roofs to evaluate the solar capacity of the company ID31.*

Figure 5.23 shows all the available roofs of the company ID31. In this case, only those areas that meet the requirements explained at the beginning can be used.

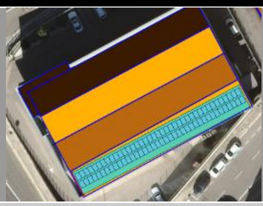
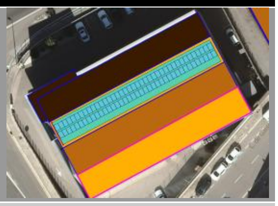
	ZONE 1	ZONE 2
		
Total Area	200 m^2	207 m^2
Number Panels	78	78
Panels Orientation	332°	332°
Roof Inclination	23°	23°
Useful Area	127,93 m^2	127,93 m^2
Annual Generated Energy	13169,66 kW·h	14044,52 kW·h

Table 5.11: *Useful roofs for the placement of panels for the Company ID31.*

The areas available for the installation of photovoltaic panels are defined in Table 5.11, with their maximum solar capacity in terms of useful area, number of panels and annual energy generated. If all the company's resources were used, it would have a solar capacity of 27214.18 kW·h/year, with the possibility of 156 photovoltaic panels installed in a useful area of 255.86 m^2, which represents 18.14% of its total surface area. The maximum peak power to be installed could be 39 kWp.

We are talking about maximum solar capacity, so it is important to know and consider the standards studied in the section Creating Energy Communities, which must be fulfilled for the installation of energy communities in industrial areas. Communities of more than 100 kWp connected to the grid for electricity compensation are not viable, i.e. companies like ID14 and ID33 will not use the maximum solar capacity available if they want to create an energy community.

5.1.3 Storage System

Selected Bateries

In order to store the energy obtained and to be able to use it when conditions are adverse, a battery system will be used. The essential characteristic of this battery system must be the ability to supply energy for several days, exactly five, without the maximum seasonal discharge depth being greater than 80% of the nominal capacity and the daily discharge depth not exceeding 15%.

According to the calculations specified in the next chapter, the selected batteries are the **20 OPzS 2500 LA** of the HOPPECKE brand with 2V each and 2500 A·h of nominal capacity. The term OPzS means: O = Ortsfest (stationary) Pz = PanZerplatte (tubular plate) S = Flüssig (flooded), and therefore they are Pb-Ac (Lead-Acid) batteries with liquid electrolyte in the form of vessels. The main characteristics are defined in Table 5.12 and in Appendix G, the data sheet can be consulted.

The container is transparent, so you can see the status of the cells and the level of the electrolyte. They are made up of covers that allow the natural evacuation of the hydrogen and oxygen freed up during gasification, as well as the periodic (normally annual) replacement of the removed water.

HOPPECKE batteries provide about 8000 charge and discharge cycles at 20% depth and 1500 cycles at 80% depth, as shown in the Fig. 5.24. The life expectancy of these batteries is up to 20 years with 20% discharge cycles. This is equivalent to a battery with 3-4 days of autonomy where each day only about 20% of the total capacity is consumed. The electrolytic reservoir and the recombination system extend the maintenance periods from five to ten times. This means that the battery is practically maintenance free or at least a smooth maintenance. In the particular case, a depth of discharge of 80% will be chosen, i.e. with 1500 cycles.

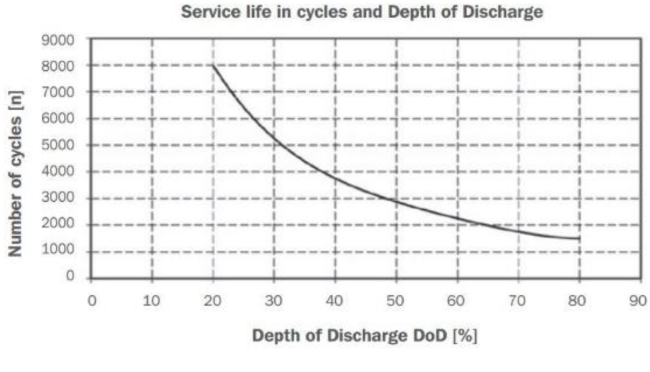


Figure 5.24: *Service Life in cycles and Depth of Discharge for batteries 20 OPzS 2500 LA.*

This model of stationary solar battery is usually used in photovoltaic and autonomous installations at 24-48V, which require a high capacity of storage with a moderate depth of discharge. Using 2 volts batteries, it is necessary to use battery banks in series of 24 units in order to supply the voltage of the global system (48V) and maintain the nominal capacity. Table 5.12 lists some of the most important features.

Important Features	Value
Nominal Voltage (V)	2
Nominal Capacity C_{10} (A·h)	2500
C_{20} (A·h)	2640
C_{100} (A·h)	3760
Internal Resistance (mΩ)	0,12
Weight (kg)	184

Table 5.12: *Characteristics of one battery used.*

Its weight is 184 kg per unit and its dimensions of 812x490x215 mm, require an appropriate and suitable location because the mixture of oxygen with hydrogen can become explosive. Batteries will receive the energy from the micro-turbine as well as from the photovoltaic panels, so it is necessary to use an inverter to transform the energy coming from the alternating current and to send the continuous current to the consumers. This will depend on the scheme: within on-grid or off-grid. In Figure 5.25, the scheme for autonomous connection is shown and in Fig. 5.26, the scheme for network connection.

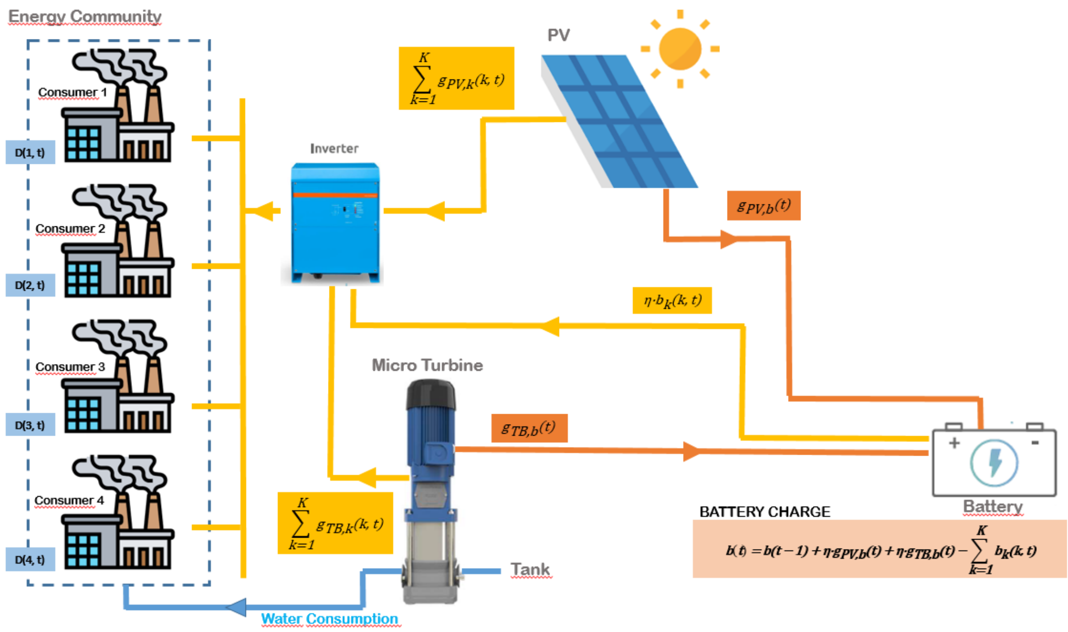


Figure 5.25: *Scheme of aff-grid or autonomous energy community.*

In this case, the inverter will transform the energy coming from the battery, direct from the turbine and photovoltaic panels (DC) up to the consumptions (AC).

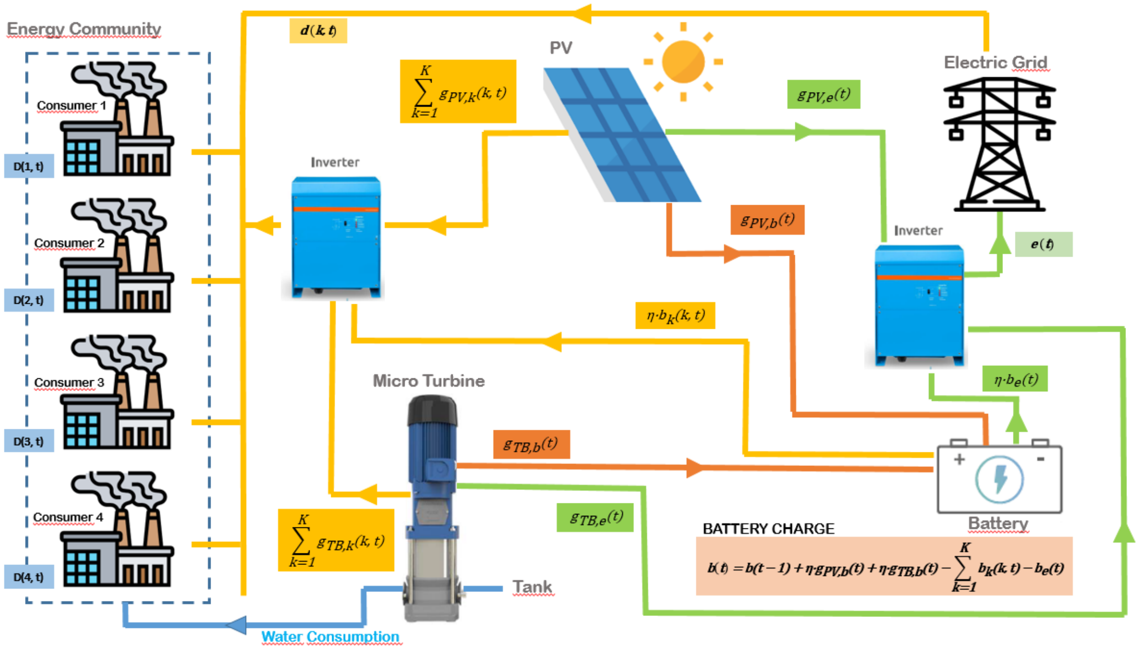


***Figure 5.26:** Scheme of on-grid energy community.*

In this case, the inverter will transform the energy in the same way as the off-grid system, but it will also transform the surplus produced by the battery, photovoltaic panel and the surplus from the battery (DC) to inject it into the electric grid (AC). It can be seen that in the latter case, two inverters are drawn but technically only one could operate the installation.

Number of bateries

To choose the optimization variable number of batteries, it is necessary to evaluate a set of basic parameters such as the nominal capacity according to the maximum daily discharge (C_d) and the nominal capacity according to the seasonal discharge (C_e).

$$C_d = \frac{L_{md}}{V_b \cdot \eta_b \cdot \mu_d} \tag{5.4}$$

$$C_e = \frac{L_{md} \cdot N_a}{V_b \cdot \eta_b \cdot \mu_e} \tag{5.5}$$

Where L_{md} is the total analyse daily consumption, V_b the battery voltage difference, η_b the battery efficiency, N_a the number of days of autonomy desired and μ_d, μ_e, the maximum daily and seasonal discharge coefficients.

All-day energy has been considered because in this way we ensure supply for the case of disconnection from the grid. In the case of on-grid, no batteries will be used because the generation will go directly to the consumption of the factories. It is also a way to reduce installation costs and increase the return on investment.

The efficiency of the battery shall be set at a constant level provided by the manufacturer and the capacity will be evaluated in the worst case, i.e. with a depth of discharge of 80% and 1500 charge/discharge cycles.

To choose the size of the battery it will be necessary that the capacity of the battery is greater than these two parameters ($B > C_d$ and $B > C_e$).

In the implemented model, it will be placed as stored energy in order to match the units, so we will have to pass from capacity units (A·h) to energy units (kW·h), in the following way:

$$E = C \cdot V_b \quad (5.6)$$

Where C will be the capacity of the entire battery pack selected in A·h.

5.1.4 Applying Optimization Model

Analyzed Particular Case

The previous optimization problem are analysed in a particular case consisting on four industrial factories or warehouses (demands of ID14, ID33, ID20 and ID31), a micro-turbine, a PV plant located in roofs of factories and a battery pack for all members. To simplify the problem, the set of buildings is considered an energy community and, later, it will be extrapolated to the other cases of the industrial estates. In Figure 5.27, the optimization problem to be analyzed is visually defined for the particular case. Firstly, there are three types of energy generation, the photovoltaic plant, the micro-turbine and the electrical network. These will supply electricity to the consumptions (lines in orange), located on the left as an energy community, and priority will always be given to the generation of renewable energies, i.e., micro-turbine and photovoltaic panels.

In addition, the renewable energy generators will be able to store a part of the surplus energy to the batteries (lines in red) and in the case of autonomous system, sell it to the electric network as surplus (green lines). Meanwhile, the battery will also serve to supply the consumption (orange line): in the case that there is no renewable generation and/or sell the stored energy at times when, there is no demand (green line). Finally, it is worth mentioning that the turbine will work when there is water consumption by the companies (blue line).

This study is located in Granollers (Spain) and specifically in two industrial states of this city. Solar data for this city (Lat. 41.60°, Lon. 2.27°), for the years 2018 and 2019 has been taken from Meteorological Service of Catalonia. Electricity price data has been taken from operating company in this place. The industrial factories' demand is extracted of equations defined in the section 3.3 Consumption Definition and them variables for each consumer (**M_2**, **turn**, **Cons_Term** and **n_work**), from various databases such as SABI or Spanish property registration.

The average yearly consumption about the study of 50 enterprises in these industrial states is 85527 kWh per enterprise. Therefore, the range of 274780 kWh to 412170 kWh is considered good for any energy community with 4 consumers (K). The electric production of the micro-turbine is calculated with software WaterGems, where it is used the hydraulic map and altitude of the zone. The maximum yearly power of micro-turbine is 0.178 kW and the hours worked during the year by every company are between 2178 and 2222, considered like hours in its average consumption. The maximum yearly power of the photovoltaic panel is 0.25 kWp.

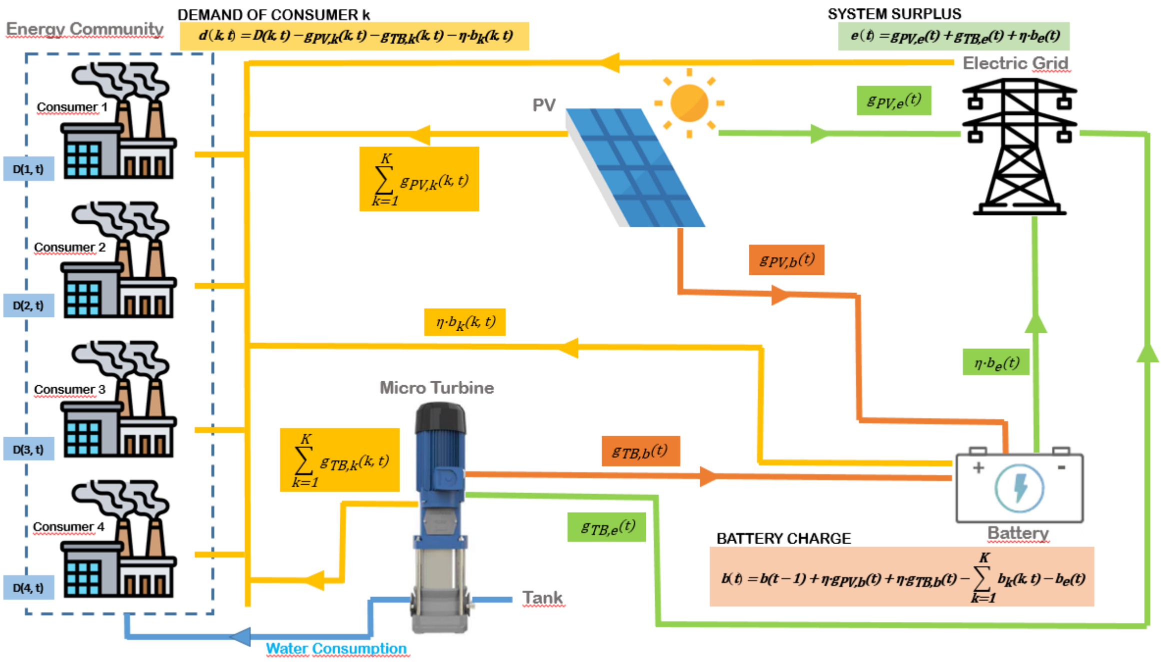


__Figure 5.27:__ Optimization model illustrated in particular case of four companies sharing energy.

Finally, the battery's depth of discharge is considered μ=0.80 (1500 cycles) and its efficiency ratio η=0.94. The particular case of on-grid system is illustrated in Fig. 5.27 and the off-grid, could be the same figure without Electric Grid and surpluses (green lines). To simplify the model, all cases and results are evaluated in one period (year).

Types of cases analysed

In the analysis of the optimization model, five well-differentiated cases will be examined in order to obtain optimal energy-sharing solutions:

1- Sharing & Connected to grid: In this case, we will have the model of energy community by which the companies will be able to share energy among themselves and all of them will be connected to the electric grid for the sale of the surplus energy. The benefits of the surplus energy will be distributed according to the policies considered by the community and the legislation.
2- Sharing & Self-consumption: This case is the same as the previous one but it will not have the connection to the electricity grid, so it will not be profitable if it generates extra energy. It will have a regulator that will stop the production of renewable energy at the peaks of less demand.
3- No sharing & Connected to grid: This energy methodology is based on the sale of surpluses to the electricity company on an individual basis, i.e. each company will have the profits separately.
4- No sharing & Self-consumption: In this case, each company will have an autonomous system, which is disconnected from the electricity network.

5- No sharing & no Self-consumption: In this case, the companies will be connected to the electricity grid as in the traditional system and without the sale of surpluses.

Input constants by case

a) Total Consumption ($\boldsymbol{D}$)

Total consumption is defined by the Consumption Definition section using a linear regression based on information obtained from a few companies. Finally, the following list is available for the four companies studied, with a total of 342107 kW·h/year.

$$\boldsymbol{D} = [153771;\ 31250;\ 37821;\ 119265]\ \mathrm{kWh/year}$$

b) Turbine Generation ($\boldsymbol{G_{TB-elect}}$)

As defined above, the turbine power will be different depending on whether one has a self-consumption model or a grid-connected model. For this reason, there will be two different generations in each case. They depends on turbine efficiency.

$$E_H = 0.178\ kW \cdot 4380\ h = 780\ \frac{\mathrm{kWh}}{\mathrm{year}}$$

$$G_{TB-ongrid} = E_H \cdot \eta_{turb} = 780 \cdot 0{,}46 = 359\ \frac{\mathrm{kWh}}{\mathrm{year}}$$

$$G_{TB-offgrid} = E_H \cdot \eta_{turb} = 780 \cdot 0{,}33 = 257\ \frac{\mathrm{kWh}}{\mathrm{year}} \quad (5.7)$$

For the calculation of the annual energy, 4380 hours per year have been used as equivalent hours and the energy will be distributed equally among all the companies.

$$\boldsymbol{G_{TB-ongrid}} = [89.75, 89.75, 89.75, 89.75]\ \ \mathrm{kWh/year}$$

$$\boldsymbol{G_{TB-offgrid}} = [64.25, 64.25, 64.25, 64.25]\ \ \mathrm{kWh/year}$$

c) PV Generation ($\boldsymbol{G_{PV}}$)

Four models have been defined for analysis depending on solar capacity:

1- Maximum Solar Capacity: the maximum number of panels that can be placed on the roofs will be installed, providing a solar power of over 100 kWp. In this case for the 4 companies we will have a total generation of 276111.11 kWh/year and a list:

$$\boldsymbol{G_{PV}} = [85035.2, 11699.13, 27214.18, 152162.6]\frac{\mathrm{kWh}}{\mathrm{year}}$$

$$N_{PV} = \mathbf{1752\ panels\ (438\ kWp)}$$

The total number of panels per roof and generation list is defined in the section 5.1.2 Photovoltaic Energy System.

2- Optimal solar capacity for autonomous system: sufficient panels will be installed to supply the right energy for self-consumption in autonomous system and including turbine generation. Therefore, the optimum panels per energy community for this installation are calculated as follows:

$$N_{PV} = \frac{(342107 - 257) \cdot \frac{1000\ \text{W}}{365\ \text{days}}}{2.49 \cdot 250 \cdot (1 - 0.152)} \cong \mathbf{1774\ panels\ (443.50\ kWp)}$$

(5.8)

A total solar generation of approximately 279263.06 kWh is thereby available. In order to divide it by companies (No Sharing case) it is necessary to analyze each case separately:

$$N_{PV,1} = \frac{153771 \cdot \frac{1000\ \text{W}}{365\ \text{days}}}{2.49 \cdot 250 \cdot (1 - 0.152)} \cong \mathbf{798\ panels\ (199.50\ kWp)}$$

$$N_{PV,2} = \frac{31250 \cdot \frac{1000\ \text{W}}{365\ \text{days}}}{2.49 \cdot 250 \cdot (1 - 0.152)} \cong \mathbf{163\ panels\ (40.75\ kWp)}$$

$$N_{PV,3} = \frac{37821 \cdot \frac{1000\ \text{W}}{365\ \text{days}}}{2.49 \cdot 250 \cdot (1 - 0.152)} \cong \mathbf{197\ panels\ (49.25\ kWp)}$$

$$N_{PV,4} = \frac{119265 \cdot \frac{1000\ \text{W}}{365\ \text{days}}}{2.49 \cdot 250 \cdot (1 - 0.152)} \cong \mathbf{619\ panels\ (154.75\ kWp)}$$

(5.9)

$$\boldsymbol{G_{PV}} = [125762.94, 25688.42, 31046.74, 97552.95]\ \frac{\text{kWh}}{\text{year}}$$

In the event that energy is not shared, this reduction in solar self-consumption will not be used, because it would no longer make sense to place one micro-turbine generator per company, and without it, the entire demand of each company would not be supplied separately.

3- Lower Solar Capacity for self-consumption of 50%: this case would not be useful for self-consumption because the total consumption of the companies would not be reached and therefore not all the energy they require could be supplied. In this case, a 50% self-consumption will be used, i. e. we will have a renewable generation of half of the required consumption.

$$N_{PV,50} = \frac{(342107 - 359) \cdot 0.5 \cdot \frac{1000\ \text{W}}{365\ \text{days}}}{2.49 \cdot 250 \cdot (1 - 0.152)} \cong \mathbf{887\ panels\ (222\ kWp)}$$

A total solar generation of approximately 139631.53 kWh is thereby available. In order to divide it by companies (No Sharing case) it is necessary to analyze each case separately:

$$N_{PV,1} = \frac{153771 \cdot 0.5 \cdot \frac{1000\ \text{W}}{365\ \text{days}}}{2.49 \cdot 250 \cdot (1 - 0.152)} \cong \mathbf{399\ panels\ (99.75\ kWp)}$$

$$N_{PV,2} = \frac{31250 \cdot 0.5 \cdot \frac{1000\ \text{W}}{365\ \text{days}}}{2.49 \cdot 250 \cdot (1 - 0.152)} \cong \mathbf{82\ panels\ (20.50\ kWp)}$$

$$N_{PV,3} = \frac{37821 \cdot 0.5 \cdot \frac{1000\ \text{W}}{365\ \text{days}}}{2.49 \cdot 250 \cdot (1 - 0.152)} \cong \mathbf{99\ panels\ (24.75\ kWp)}$$

$$N_{PV,4} = \frac{119265 \cdot 0.5 \cdot \frac{1000\ \text{W}}{365\ \text{days}}}{2.49 \cdot 250 \cdot (1 - 0.152)} \cong \mathbf{310\ panels\ (77.50\ kWp)}$$

(5.10)

$$\boldsymbol{G_{PV}} = [62881.47, 12844.21, 15523.37, 48776.48]\,\frac{\text{kWh}}{\text{year}}$$

4- Lower Solar Capacity for self-consumption of 25%: this case would not be useful for self-consumption because the total consumption of the companies would not be reached and therefore not all the energy they require could be supplied. In this case, a 25% self-consumption will be used, i. e. we will have a renewable generation of half of the required consumption.

$$N_{PV,25} = \frac{(342107 - 359) \cdot 0.25 \cdot \frac{1000\ \text{W}}{365\ \text{days}}}{2.49 \cdot 250 \cdot (1 - 0.152)} \cong \mathbf{444\ panels\ (111\ kWp)}$$

A total solar generation of approximately 69815.77 kWh is thereby available. In order to divide it by companies (No Sharing case) it is necessary to analyze each case separately:

$$N_{PV,1} = \frac{153771 \cdot 0.25 \cdot \frac{1000\ \text{W}}{365\ \text{days}}}{2.49 \cdot 250 \cdot (1 - 0.152)} \cong \mathbf{200\ panels\ (50\ kWp)}$$

$$N_{PV,2} = \frac{31250 \cdot 0.25 \cdot \frac{1000\ \text{W}}{365\ \text{days}}}{2.49 \cdot 250 \cdot (1 - 0.152)} \cong \mathbf{41\ panels\ (10.25\ kWp)}$$

$$N_{PV,3} = \frac{37821 \cdot 0.25 \cdot \frac{1000\ \text{W}}{365\ \text{days}}}{2.49 \cdot 250 \cdot (1 - 0.152)} \cong \mathbf{50\ panels\ (12.50\ kWp)}$$

$$N_{PV,4} = \frac{119265 \cdot 0.25 \cdot \frac{1000\ \text{W}}{365\ \text{days}}}{2.49 \cdot 250 \cdot (1 - 0.152)} \cong \mathbf{155\ panels\ (38.75\ kWp)}$$

(5.11)

$$\boldsymbol{G_{PV}} = [31440.74, 6422.10, 15523.37, 48776.48]\,\frac{\text{kWh}}{\text{year}}$$

Depending on the case studied, one model or another will be applied. In Table 5.13, a summary of all installed powers is defined and divided by case and model.

CASE / MODEL	1		2		3		4	
	$P_{PV}\ (kWp)$	$P_{TB}\ (kW)$	$P_{PV}\ (kWp)$	$P_{TB}\ (kW)$	$P_{PV}\ (kWp)$	$P_{TB}\ (kW)$	$P_{PV}\ (kWp)$	$P_{TB}\ (kW)$
1-SHARING & GRID	438	0.178	-	-	221.50	0.178	110.75	0,178
2-SHARING & SELF-CONSUMPTION	-	-	443	0,178	-	-	-	-
3-NO SHARING & GRID	438	0	-	-	283.50	0	121.75	0
4-NO SHARING & SELF-CONSUMPTION	-	-	444.25	0	-	-	-	-
5-NO SHARING & NOTHING	-	-	-	-	-	-	-	-

Table 5.13: *Power installed and percentage by case and model.*

d) Battery ($\boldsymbol{B}$)

To define the capacity of the battery for self-consumption options, it is necessary to calculate the seasonal (for 5 days discharge) and daily nominal capacities:

$$C_d = \frac{L_{md}}{V_b \cdot \eta_b \cdot \mu_d} = \frac{342107 \cdot \frac{1000\, W}{365\, days}}{48 \cdot 0.94 \cdot 0.15} = 138486.92 \text{ Ah}$$

$$C_e = \frac{L_{md} \cdot N_a}{V_b \cdot \eta_b \cdot \mu_e} = \frac{342107 \cdot \frac{1000\, W}{365\, days} \cdot 5}{48 \cdot 0.94 \cdot 0.80} = 129831.48 \text{ Ah}$$

(5.12)

The greater value of these will be the minimum capacity for the batteries, so we will choose the value of 138486.92 A·h. In order to have the same units of energy in the model, it is necessary to change the capacity to daily stored energy:

$$E = C \cdot V_b \cdot \frac{1 \text{ kW}}{1000 \text{ W}} = 138486.92 \cdot 48 \cdot \frac{1 \text{ kW}}{1000 \text{ W} \cdot 5 \text{ days}} = 1329{,}48\ \frac{\text{kWh}}{\text{day}}$$

(5.13)

Finally we get the energy that you can store for a year:

$$\boldsymbol{B} = E \cdot 365\, days = 485258.16\ \frac{\text{kWh}}{\text{year}}$$

(5.14)

e) Electricity costs ($\boldsymbol{C_D}$, $\boldsymbol{C_E}$)

To simplify the problem, the prices of the electricity consumed by the company and the surplus will be set as constant throughout the year with an average value per kW·h approximately and also for contracted powers over 15 kW.

$$\boldsymbol{C_D = 0{,}14 \frac{€}{kWh}} \qquad \boldsymbol{C_E = 0{,}06 \frac{€}{kWh}}$$

5.2 Final Results

To evaluate every case studied is important to do this double analysis: economic and environmental.

5.2.1 Environmental Analysis

CO_2 Emissions Savings

The calculation of CO_2 savings has been based on internationally accepted standard emission factors for electricity generation. Thus, the percentage of CO_2 emission considered is equivalent to 0.563 kg / kWh. The CO_2 emission caused by the production of energy with solar panels has been considered, according to GEMIS 4.6[10]:

[10] GEMIS - Global Emissions Model for integrated Systems: a public domain life cycle and material flow analysis model and database that IINAS provides freely.

- CO_2 emissions in mono-crystalline systems (15% efficiency): 0.135 kg / kWh
- CO_2 emissions in polycrystalline systems (12% efficiency): 0.105 kg / kWh
- CO_2 emissions in amorphous systems (9% efficiency): 0.05088 kg / kWh

Consequently, the resulting CO_2 reduction obtained and applied per type of module is:

- CO_2 reduction in mono-crystalline systems (15% efficiency): 0.428 kg / kWh
- CO_2 reduction in polycrystalline systems (12% efficiency): 0.458 kg / kWh
- CO_2 reduction in amorphous systems (9% efficiency): 0.512 kg / kWh

These values have been applied for the global calculation of the CO_2 reduction in the city and more specifically for mono-crystalline systems because panels with an efficiency of 15.2% are used.

Grants for the sale of CO_2 emissions

As indicated in Real Decreto 616/2017[11] , of 16th June, which sets out the direct granting of subsidies to unique projects of local entities that promote the transition to a low-carbon economy within the framework of the FEDER Operational Programme for Sustainable Growth 2014-2020, a bonus is set for the reduction of CO_2 emissions of approximately 0.19 euros per tonne. Therefore, for the self-consumption options, the benefit for the reduction of emissions will be directly the consumption of the companies by the amount of the module type of the previous section, i. e:

$$g_{CO2} = \sum_{k=1}^{K} D \cdot 0{,}428 \frac{\text{kg}}{\text{kWh}} \cdot \frac{1\ \text{Tm}}{1000\ \text{kg}} \cdot \frac{0{,}19€}{1\ \text{Tm}} \tag{5.15}$$

For grid-connected options, the benefit will be according to the difference in energy generated with renewable energies:

$$g_{CO2} = \left[\sum_{k=1}^{K} D - \sum_{k=1}^{K} d(k,t)\right] \cdot 0{,}428 \frac{\text{kg}}{\text{kWh}} \cdot \frac{1\ \text{Tm}}{1000\ \text{kg}} \cdot \frac{0{,}19€}{1\ \text{Tm}} \tag{5.16}$$

Cases results

In the following results placed in the tables, they will be divided by the installed solar capacity. The extensive results returned by the programme are in the latest Annex J.

[11] Real Decreto 616/2017: Decree published by the organ of the Ministry of Industry, Energy and Digital Agenda of Spain.

a) Case 1 – Sharing & Connected to grid

	MAXIMUM CAPACITY	LOWER CAP (50%)	LOWER CAP (25%)
Demand [kWh]	342107		
Renewable Energy to customers [kWh]	241299	137914	69712
Battery Energy to customers [kWh]	0	0	0
Total Renewable Energy [kWh]	241299	137914	69712
Electric company to customers [kWh]	105404	206489	273173
Surplus [kWh]	30648	0	0
Annual CO_2 Profit [€]	19.25	11.03	5.61
CO_2 Reduction [Tm CO_2]	101.32	58.05	29.53

Table 5.14: *Environmental results of Case 1.*

An energy community that is connected to the grid will always yield current as surplus, unless lower solar capacity is installed. In this case, it is noted that if the maximum capacity is used, it would be more reasonable to use an off-grid system because it will use less electricity from the distribution company. On an environmental perspective, it has been demonstrated in Table 5.14 that the more renewable energy capacity installed, the more CO_2 reductions are obtained.

b) Case 2 – Sharing & Self-consumption

For an energy community, with an off-grid system, only optimal capacities can be compared because the right panels need to be installed to reach 100% self-consumption, no more and no less. Surplus energy cannot be sold because it is not connected to the grid, so there is no point in installing more panels. On an environmental perspective and according to Table 5.15, the maximum reduction of CO_2 emissions is obtained, because all consumption is generated with renewable energies.

	OPTIM CAPACITY
Demand [kWh]	342107
Total Renewable Energy [kWh]	342107
Electric company to customers [kWh]	0
Surplus [kWh]	0
Annual CO_2 Profit [€]	27.82
CO_2 Reduction [Tm CO_2]	146.42

Table 5.15: *Environmental results of Case 2.*

c) Case 3 – No sharing & Connected to grid

In the case of non-participation, each company must be analysed separately. Each table in Appendix J.3 shows the results according to the installed solar capacity. From an environmental perspective, Table J.5 and J.7, shows how the total CO_2 reduction of the four companies is completely equal to the case of sharing (energy community). On the other hand, if we look at the most economically solar capacity (25% of self-consumption) located in Table J.9, the Sharing case has a reduction of 29.53 tons of the total CO_2 emissions, while individually, a value of 42.37. From 50% of self-consumption and lower values, there is no sale of surplus because when the installation generates energy (during the sunny day), the company exclusively consumes it all.

d) Case 4 – No sharing & Self-consumption

In Table 5.16, the final environmental and energy results of the 4 companies are shown separately and with a 100% autonomous installation. As none of them consume electricity from the electricity company, they have the same ratio of emissions reduction as in the case of joining as an energy community.

	OPTIM CAPACITY				
Company	**MONDELEZ**	**RELEM**	**AIRNOU**	**PAVER**	**TOTAL**
Demand [kWh]	153771	31250	37821	119265	**342107**
Total Renewable Energy [kWh]	153771	31250	37821	119265	**342107**
Electric company to customers [kWh]	0	0	0	0	**0**
Surplus [kWh]	0	0	0	0	**0**
Annual CO_2 Profit [€]	12.51	2.54	3.08	9.70	**27.83**
CO_2 Reduction [Tm CO_2]	65.84	13.37	16.21	51.05	**146.47**

Table 5.16: *Environmental results of Case 4.*

Environmental and energy evaluation

From the results obtained, the following conclusive premises can be observed:

1- The sum of the electric energy supplied by the company is significantly higher in the case of not forming energy communities. Comparing Table 5.14 of Case 1 with Tables J.5 and J.7 of Case 3 can see this. Much more money is charged to individual companies than when they join together through the hybrid system. For table J.9 (25% self-consumption), however, the opposite is true.

2- In the No sharing model, as a consequence of the first premise in Tables J.5 and J.7, renewable energy sources are used less, thus increasing energy costs.

3- For the self-consumption models, as it is obvious, the concept of buying electric energy will always be saved, having an installation that covers the demand. These cases will always reduce the maximum number of CO_2 emissions, and will only be equalized in those cases where the installed solar power is much higher than the optimal case (maximum solar capacity model).

4- The reduction of CO_2 with the concept of No Sharing (separate companies), will usually be lower than the Sharing model (energy communities), so energy selfishness will negatively affect the environment. In this case, it can be reduced between 1 and 4% less depending on the installed power. As the installed power increases, it varies more from one model to another. Comparing Table 5.14 of Case 1 with Tables J.5 and J.7 of Case 3, can see this.

5.2.2 Economic Analysis

Turbine costs

The cost of the turbine can be calculated approximately according to the following equation obtained from the source [5] (**D. Novara, 2019**), and depends exclusively on the power used:

$$c_{TB} = P[kW] \cdot 826{,}42 \cdot P[kW]^{-0{,}292} \tag{5.17}$$

Normally in the field of hydraulics, there are few purchase price figures for PATs and if they exist it is discordant and outdated. This lack of information is probably a serious obstacle to a more widespread application of micro-turbines in the water networks of energy communities. To overcome this limitation, data from 343 turbines and 286 generators were collected to show graphically and analytically how the purchase price of PATs varies in different nominal powers and hydraulic conditions. In addition, a set of equations including equation 5.17 was developed to allow designers to predict the PATs and generator cost from the nominal flow rate, the available head and implicitly the micro-turbine power. Using this equation, one can approximate the total cost of installing the turbine, including the generator.

PV installation costs

As is logical, one has to take into account that the costs of a photovoltaic panel installation can be affected by many variables, such as the quality of the products, the type of equipment required, the particularities of each project, etc. The prices shown in Table 5.17 are approximate and are a guide to how the Spanish solar panel price market will move according to the size of the installation in 2019-2020.

Size of Installation	Average Price of Installation with IVA (21%)	Average Price of Installation without IVA	Average Price in €/Wp
2 kW	5.120,00 €	4.231,40 €	2,12 € per Wp
3 kW	7.280,00 €	6.016,53 €	2,01 € per Wp
4 kW	9.670,00 €	7.991,74 €	2,00 € per Wp
5 kW	12.050,00 €	9.958,68 €	1,99 € per Wp
6 kW	14.160,00 €	11.702,48 €	1,95 € per Wp
7 kW	16.170,00 €	13.363,64 €	1,91 € per Wp
8 kW	18.210,00 €	15.049,59 €	1,88 € per Wp
10 kW	22.600,00 €	18.677,69 €	1,87 € per Wp
12 kW	26.930,00 €	22.256,20 €	1,85 € per Wp
15 kW	33.400,00 €	27.603,31 €	1,84 € per Wp
20 kW	40.200,00 €	33.223,14 €	1,66 € per Wp
25 kW	49.000,00 €	40.495,87 €	1,62 € per Wp

Table 5.17: *Approximate prices for solar panel installations in 2019-2020.*

The factors that affect the price of a self-consumption system with photovoltaic panels are:

1. **The price of the photovoltaic panels used**: Quality has a major role to play here. Less quality means less price, but also less performance and less profitability in the medium term.
2. **The size of the installation**: Logically, like any product, with greater purchase volume, lower prices. A 3kW solar panel project will be closer to 1.5-2 €/Wp than a 1 MW one.

3. **Subsidies and grants**: If the installation has received a grant or subsidy, which are very frequent since the beginning of 2019, the price can easily be reduced by 30-50%, depending on each case.

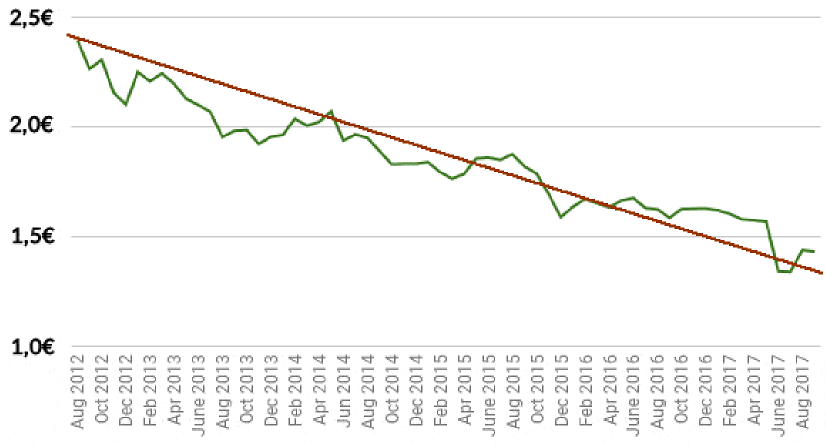


Figure 5.28: *Evolution of the installation PV's cost.*

It is true, and can be shown by Fig. 5.28, that the cost of a PV system is becoming increasingly affordable for customers. Practically since 2012, it has been decreasing at a high rate to what is explained in Table 5.17, i.e. at present. The following table is an estimate of the price of each piece of equipment needed to install a solar farm:

Equipment	Function	Price ranges
Photovoltaic Panels	Transforming solar energy into electricity that will go to the solar inverter.	90-250€/panel
Inverter	It transforms direct current into alternating current.	800-3.000€
Structure	To install the photovoltaic panel on the roof or ground.	45-60€ per panel
Two-way counter	For the registration of consumption and production of the dwelling.	250-350€
DC and AC protection panel	Protections for the photovoltaic system for both alternating and direct current.	400-500€
Legalization	Registration and legalization of the installation	300-400€
Assembly of the installation and other materials	Cost of installation, wiring, trays...	Depending on each project

Table 5.18: *Price range of the equipment needed in a photovoltaic system.*

According to this market study, it was decided to estimate the price of the photovoltaic installations based on euros per installed watt peak, using the approximation criteria in Fig. 5.29 and the respective power ranges.

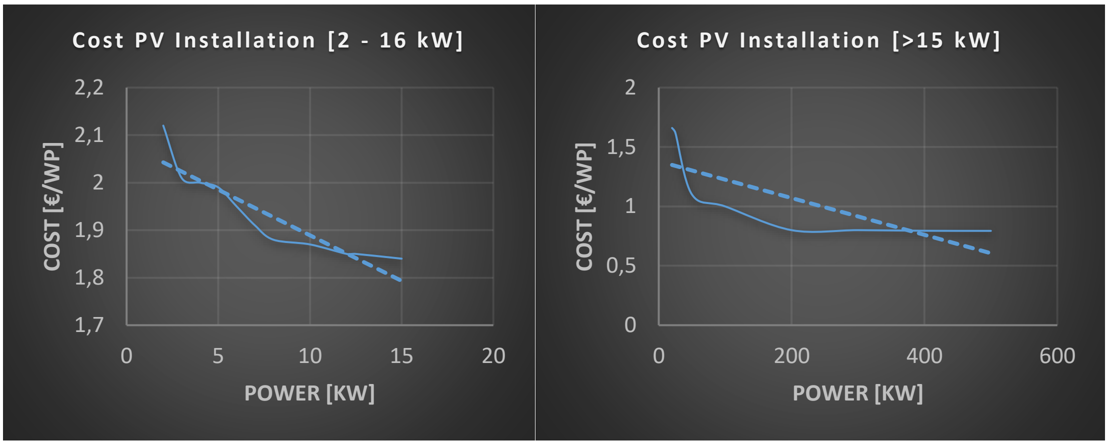


Figure 5.29: *Costs of PV installation by different ranges of Power.*

a) Installations of **12,5 kW** → 1,85€/Wp
b) Installations of **25 kW** → 1,62 €/Wp
c) Installations of **50 kW** → 1,1 €/Wp
d) Installations of **100 kW** → 1 €/Wp
e) Installations of more than **200 kW** → 0,8 €/Wp

The cost of the batteries (C_{Bat}) will be approximate according to the model defined in section 5.1.3 and will be applied only for off-grid cases. Therefore, for a quantity of six glasses of 2 volts each (12 V), with a total capacity of 3760 Ah, the cost will be always approximately 400€ for kWh of energy, depending of storage energy that will be needed. So it will be controlled by the following equation 5.18:

$$C_{Bat} = C \cdot V_b \cdot \frac{1\text{ kW}}{1000\text{ W}} \cdot 400€ \quad (5.18)$$

Cases analysis

Each case explained has been economically analysed with a mathematical optimization software and from the defined optimization system. From this, variables such as the first year's profit, the initial investment, the payback and the rate of return on investment (IRR) have been evaluated.

This profitability has been calculated at 25 years, due to solar panels having an average useful life of more than 20-25 years. If the amortization is returned in the first 10 years, the photovoltaic profitability will be very high. Moreover, the savings can be noticed from the first moment we start using the panels. The profitability of solar panels is undeniable. It only remains that society, policies are adapted to this new era, and their use is increased.

The main reasons why photovoltaic solar energy is profitable are:

- Fuel price: It does not use fossil fuels whose price is increasing due to their progressive lack.
- No maintenance: It requires practically no maintenance, only cleaning.
- Useful life: Can exceed 25 years and offer resistance to adverse weather conditions.

- Decreasing price: The price of solar panels decreases progressively as the installations increase.
- Subsidies: Existence of subsidies for the installation of solar panels.
- Return on investment: The investment is returned in the medium term and offers a reduction in consumption from the outset.

The benefits of the installation (g_{ins}) are calculated from two main factors, depending on the function to be optimized. These are the sale of surplus energy to the electric company ($c1$) and the net benefit of the energy generated from renewables that will no longer be paid to the supplier ($c2$).

$$c1 = \sum_{t=1}^{T} (C_E(t) \cdot e(t)) \tag{5.19}$$

$$c2 = [\sum_{k=1}^{K} D - \sum_{k=1}^{K} d(k, t)] \cdot C_D \tag{5.20}$$

In these factors the environmental benefit or subsidy for the reduction of CO_2 emissions, evaluated in the previous section, will be added (g_{CO2}). This profit will increase approximately 1% per year due to the increase in the cost of electricity (C_D) and will form the cash flow.

$$g_{ins} = c1 + c2 + g_{CO2} \tag{5.21}$$

The initial investment or total costs (c_{ins}) will be the costs of the photovoltaic installation (C_{PV}) added to the costs of the installation of the turbine (C_{TB}) and the battery costs (C_{Bat}).

To consult the results, go to the section Results in the Appendix J and you will find a summary table of the profitability and year of return on investment (payback) for each case analysed.

a) Case 1 – Sharing & Connected to grid: Appendix J.1
b) Case 2 – Sharing & Self-consumption: Appendix J.2
c) Case 3 – No sharing & Connected to grid: Appendix J.3
d) Case 4 – No sharing & Self-consumption: Appendix J.4

Economic evaluation

From the financial results obtained, the following conclusive premises can be observed:

(i) As a general criterion, the Non-Sharing model is destined to end in the future. Although the costs in photovoltaic material such as batteries, inverters, panels, etc, tend to decrease, the return on investment for individual investing companies will always be lower than if it is applied as an energy community model.

The profitability of disconnecting from the grid (self-consumption) on an individual basis is approximately -6.23% (54 years) calculated over 25 years. If it is applied as an energy community, it can be increased a little bit (-5.79% and Payback 51 years), but it is still not feasible for companies. For energy communities that do not want to be totally disconnected from the grid, in this case, a return of at least 10 years is achieved on average. This gives a safe solution for those companies that are using energy for many hours and avoiding demand peaks that are difficult to control with self-consumption.

(ii) It can be seen that, in all cases of Non-Sharing and off-grid connection, the average payback is over 52 years for all companies, because the initial investment is very high due to the use of batteries, which are the most expensive element so far. In these cases, there is no depreciation of the solar panels because their useful life does not usually exceed 20 - 25 years and when they stop working, the investment would still be paid for.

For both Non-Sharing and the formation of an energy community, the on-grid model is always a more viable option than autonomous system, talking in long-term financial terms, and in most cases the payback is lower. It is also safer, if we talk about technical issues, where it is more complicated to carry out a disconnection of for example an industrial factory, due to its power and demand peaks. In addition, the off-grid option is likely to require many panels and not enough roof space for placement. We are talking about large amounts of energy, to be recovered in very little space.

(iii) It should be noted, that although micro turbines generate little energy compared to photovoltaic panels, it is a way to recover lost water resources and help reduce the number of final panels. In the case of No Sharing, more panels will always be used because it is not possible to take advantage of this methodology. The profitability of the investment is improved always because the cost of the micro turbine compared to its generation is significant, so it is recommended to use this type of device, whenever possible, which promote energy recovery and reduction of photovoltaic panel materials.

(iv) Finally, and according to the above analysis, for the particular study it would be recommended to implement the Sharing model starting progressively with an installation connected to the electricity grid and investing in the optimal model of panels covering 50% the demand (self-consumption of 50%). This model gives a return of 10.41% over 25 years and a rate of return on investment of 9 years.

Chapter 7

6 Conclusions

The main estimated conclusions of this thesis are based on promoting changes in the peripheral areas of industrial cities by proving that the energy system can be improved by means of hybrid models and energy sharing between the companies that are the main consumers.

First of all, it is interesting to establish the creation of the energy management role in local administrations to promote the energy transition in industrial areas. In this project, it has been shown that obtaining information on consumption by companies has been a difficult milestone to achieve, due to the lack of time they spend on external factors such as improvements in their energy systems. This new figure could help a lot in issues of joining the companies with the administration and encourage projects like the one developed in this research.

The statistical study carried out will facilitate an extrapolation of the results to new peripheral areas of similar cities and will also serve as a guide to follow for the study of the creation of energy communities. At present, the technical and legal resources provided by the administration are ambiguous and not sufficiently accurate to carry out this important energy transformation that must be applied in the real world. Therefore, it has been proved the need of creating specific technical guides for energy communities, by the administrative entities in countries like Spain and Portugal.

On the other hand, it has been confirmed that the option of self-consumption is the best solution at an environmental scale in the long-term, although in the case of industrial areas or peripheral zones with large consumers, at a technical scale it could be a complex step in energy transformation. There are many agents involved in a change like this, so each particular case would have to be analysed to define an optimal solution. The model developed in this project will help you to extract conclusions from these particular cases but before it is necessary to know the consumption, solar generation capacities and resources of each company studied.

In addition, it has been identified that the use of micro-turbines always improves the investment return because their installation cost is significant compared to the energy generated, [5]. It is a good model to implement, because it takes advantage of an energy that is implicit in any industrial area and uses the resources of others to contribute to all (Circular Economy). Not only in the case of micro-turbines in the hydraulic network, but in any hybrid system will generate an extra benefit to the energy community, in economic and environmental terms.

It is worth adding that, for models with large electricity consumers, it is advisable to start with a solution connected to the electricity grid (on-grid), as the transition to off-grid self-consumption could cause irreparable technical failures for companies. According to the criterion developed in this project, it is important to move towards energy transition step by step and not to want to take huge steps to obtain milestones quickly and without coherence. Thus, we should start by connecting those energy communities with large consumption, such as industrial companies, to the electricity network. Saving the cost of batteries will allow companies to have a sufficiently consistent payback period to initiate changes towards energy transition. The total disconnection would be a good incentive for communities of neighbours or administrative buildings of daily use that consume much less energy than the industry sector.

Finally, in this thesis it has been tried to prove that, if sharing is enhanced, renewable energies are also promoted together with the implicit market and, in fact, it helps in the contribution towards a more sustainable world with the help of the reduction of CO_2 emissions in the current processes of electricity generation.

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Appendix A

A Energy Information and tables

The following tables are related to chapter 3 (Background):

Table A.1 **BALANCE SHEET OF TOTAL ELECTRICAL ENERGY IN SPAIN**

GWh	2016	2017	Δ%
Production of conventional technologies (1)			
Hydroelectric	33.343	16.713	-49,9
Thermoelectric	73.516	89.504	21,7
Nuclear Thermoelectric	56.099	55.609	-0,9
Total conventional technologies	**162.958**	**161.826**	**-0,7**
Production under the scheme with specific remuneration (1)			
Renewables and waste	73.415	72.649	-1,0
Cogeneration and waste treatment	25.907	28.170	8,7
Total system with specific remuneration	**99.321**	**100.820**	**1,5**
Net production	**262.279**	**262.645**	**0,1**
Consumption in pumping	4.819	3.675	-23,7
International balance	7.667	9.171	19,6
Energy available to the market	**265.127**	**268.140**	**1,1**
Transport and distribution losses	26.634	26.937	1,1
Net Consumption [GWh/year]	**238.493**	**241.204**	**1,1**

% = Percentage change from last year

(1) Estimation

Source: UNESA, REE and CNMC. Provisional data

Medium Power Demand [MW]	**27.225**	**27.535**
	Δ%	1,00516968

***Table A.1**: Balance sheet of total electrical energy in Spain.*

Table A.2

2017 GWh	Cataluña	Total Spain
Hydraulics	3.720	**18.364**
Turbination pumping	114	**2.249**
Nuclear	24.233	**55.609**
Coal	0	**45.196**
Fuel / gas	0	**7.011**
Combined cycle	7.893	**37.296**

Hydroelectric	0	**20**
Wind	2.825	**47.897**
Solar photovoltaic	420	**8.385**
Solar thermal power	87	**5.348**
Other renewables	191	**3.614**
Cogeneration	5.082	**28.170**
Non-renewable waste	145	**2.608**
Renewable waste	141	**877**
Net generation	**44.852**	**262.645**
Consumption in pumping	-165	**-3.675**
Exchange Balance (1)	2.966	**9.171**
Demand b.c.	**47.652**	**268.140**
Δ % 2017 / 2016	**2,4**	**1,2**

Table A.2: *Energy balance in Spain by regions.*

Table A.3

HISTORICAL SERIES OF NET ELECTRICITY CONSUMPTION IN SPAIN

	Milions kWh	Δ%
1960	14.625	8,4
1970	45.300	10,4
1980	92.006	4,6
1985	105.579	2,9
1990	129.161	3,0
1995	150.289	3,6
1996	154.928	3,1
1997	162.338	4,8
1998	174.316	7,4
1999	186.473	7,0
2000	197.524	5,9
2001	209.065	5,8
2002	215.650	3,1
2003	230.897	7,1
2004	242.077	4,8
2005	252.857	4,5
2006	260.474	3,0
2007	267.831	2,8
2008	268.534	0,3
2009	253.079	-5,8
2010	256.629	1,4
2011	248.656	-3,1
2012	245.687	-1,2
2013	235.986	-3,9
2014	233.321	-1,1
2015	236.651	1,4
2016	238.493	0,8
2017	241.204	1,1

Δ % = Percentage change from previous year

Table A.3: *Historical series of net electricity consumption in Spain.*

Appendix B

B Meteorological Information and Tables

The following tables are related to chapter Renewable sources in the area. All data it was obtained by day and calculated as monthly average:

B.1 Monthly meteorological data

	TM	TX	TN	HRM	RS24h	VVM10	DVM10	VVX10	DVVX10
Jan-18	9,63	15,81	4,24	74,03	8,62	1,64	193,45	7,86	227,39
Feb-18	6,56	12,11	1,86	74,14	9,35	1,75	134,14	7,81	150,46
Mar-18	10,82	17,12	5,15	66,77	16,01	2,28	213,74	10,76	254,00
Apr-18	14,97	21,32	9,13	69,00	19,54	2,06	147,50	9,40	159,77
May-18	17,28	23,76	12,04	71,39	20,32	1,85	139,90	8,27	151,42
Jun-18	22,37	28,18	16,89	63,83	25,38	1,88	154,57	8,58	163,37
Jul-18	25,66	32,01	19,61	61,26	26,25	1,99	141,32	8,64	156,74
Aug-18	25,71	32,01	20,46	64,52	20,90	1,89	144,03	8,77	155,90
Sep-18	22,59	28,96	17,65	72,83	16,92	1,75	121,23	8,04	147,13
Oct-18	16,87	22,99	11,99	77,61	11,48	1,80	126,48	8,30	155,19
Nov-18	11,80	17,03	7,62	85,57	7,44	1,58	125,83	6,70	160,80
Des-18	8,73	15,83	3,81	84,32	7,45	1,00	163,35	5,03	223,10
Jan-19	6,26	13,73	0,40	70,16	9,03	1,45	191,52	7,28	233,68
Feb-19	9,39	18,27	2,47	68,89	13,24	1,22	165,82	6,41	203,50
Mar-19	12,04	19,93	5,26	62,90	18,02	1,71	149,06	8,55	170,68
Apr-19	13,46	19,21	8,63	67,77	17,29	2,46	133,03	9,90	150,00
May-19	16,08	22,08	10,55	70,84	22,99	1,94	154,06	8,66	168,68
Jun-19	22,63	29,76	15,76	55,53	27,49	2,14	154,30	8,89	158,10
Jul-19	25,79	32,15	20,01	63,74	25,25	1,88	145,03	9,01	186,58
Aug-19	25,49	31,90	19,89	62,90	23,11	1,87	138,90	8,41	160,74
Sep-19	21,97	28,27	16,69	67,93	18,11	2,00	124,53	8,72	141,53
Oct-19	18,15	24,35	13,24	77,11	12,02	1,70	151,71	8,05	189,18

Table B.1*: Monthly meteorological data (year 2018 and 2019)*

	TM	TX	TN	HRM	RS24h	VVM10	DVM10	VVX10	DVVX10
January	7,95	14,77	2,32	72,10	8,82	1,54	192,48	7,57	230,53
February	7,98	15,19	2,16	71,52	11,30	1,49	149,98	7,11	176,98
March	11,43	18,52	5,21	64,84	17,01	1,99	181,40	9,66	212,34
April	14,22	20,27	8,88	68,38	18,41	2,26	140,27	9,65	154,88
May	16,68	22,92	11,30	71,11	21,65	1,90	146,98	8,46	160,05
June	22,50	28,97	16,33	59,68	26,43	2,01	154,43	8,73	160,73
July	25,72	32,08	19,81	62,50	25,75	1,94	143,18	8,83	171,66
August	25,60	31,95	20,18	63,71	22,00	1,88	141,47	8,59	158,32
September	22,28	28,61	17,17	70,38	17,51	1,87	122,88	8,38	144,33
October	17,51	23,67	12,61	77,36	11,75	1,75	139,10	8,18	172,19
November	11,80	17,03	7,62	85,57	7,44	1,58	125,83	6,70	160,80
December	8,73	15,83	3,81	84,32	7,45	1,00	163,35	5,03	223,10

Table B.2: *Average of Monthly meteorological data*

B.2 Caption

Acronym	Variable	Unit
TM	Daily average temperature	°C
TX	Maximum daily temperature	°C
TN	Minimum daily temperature	°C
HRM	Daily average relative humidity	%
RS24h	Daily global solar radiation	MJ/m^2
VVM10	Daily wind speed at 10 meters high	m/s
DVM10	Daily wind direction 10 meters high	°
VVX10	Maximum daily wind speed at 10 metres height	m/s
DVVX10	Direction of the maximum daily wind speed at 10 metres height	°

Table B.3: *Caption and metrics.*

Appendix C

C Companies Information

The following tables are the obtained information of 50 companies located in industrial areas studied:

ID	Commercial Name	Industrial Area	Workers	Turnover	Building superficie [m2]	Annual thermal consumption [kWh]	Annual water consumption [m3]	Annual Expenses in Salaries [€]	Annual Expenses in Electricity [€]	Annual Expenses in Water [€]	Annual Expenses in Supplies [€]	NW [€ Electricity x capita]	Altitude [m]
1	RUBBERMAT - TALLERES INGENIERÍA MECÁNICA	FONT DEL RADIUM	20	1500000	2600	183222	1600	368.609,18 €	8.023,58 €	1.633,62 €	9.657,20 €	401,18 €	196,7
2	PLASTICBAND	FONT DEL RADIUM	38	4630000	1763	505570,221	4270	1.442.379,49 €	5.457,49 €	4.353,28 €	9.810,77 €	143,62 €	170,4
3	KARCHER, SA	FONT DEL RADIUM	80	38614000	1525	107466,75	3820	7.276.068,45 €	4.727,82 €	3.894,91 €	8.622,73 €	59,10 €	170,4
4	TRANSPORTES JUBERA	FONT DEL RADIUM	15	2000000	964	0	1400	834.285,14 €	3.007,89 €	1.429,90 €	4.437,79 €	200,53 €	162
5	ATI ASESORIA TECNICA INDUSTRIAL	FONT DEL RADIUM	12	1301000	560	164502,155	1150	491.427,89 €	1.769,30 €	1.175,25 €	2.944,55 €	147,44 €	180
6	FICALTRANS SL	FONT DEL RADIUM	10	2521684	430	0	690	699.040,03 €	1.370,74 €	681,72 €	2.052,46 €	137,07 €	162
7	ABRATOOLS	FONT DEL RADIUM	50	90000000	1635	0	1950	880.239,45 €	5.065,06 €	1.990,13 €	7.055,19 €	101,30 €	162
8	AUTOMOBILS PRUNA, SA	COLL DE LA MANYA	29	2844000	5460	0	6850	1.621.099,55 €	16.791,84 €	6.981,27 €	23.773,11 €	579,03 €	135,9
9	MAINCA	COLL DE LA MANYA	27	6408000	1674	117966,78	1380	1.314.508,00 €	5.184,63 €	1.409,53 €	6.594,16 €	192,02 €	167
10	FALCK VL SERVICIOS SANITARIOS	COLL DE LA MANYA	200	70000000	836	0	4520	39.595.000,00 €	2.615,47 €	4.607,93 €	7.223,40 €	13,08 €	164,1
11	INDUSTRIAS MURTRA S.A.	COLL DE LA MANYA	200	65000000	5084	10683029,5	600	5.564.000,00 €	15.639,09 €	593,30 €	16.232,39 €	78,20 €	139
12	SHINGELS, SA	COLL DE LA MANYA	30	18557000	2975	789288,626	4800	2.572.735,90 €	9.173,27 €	4.893,14 €	14.066,41 €	305,78 €	168,1

13	CRICURSA	COLL DE LA MANYA	100	14878000	9860	0	17475	6.534.877,00 €	30.281,47 €	17.803,90 €	48.085,37 €	302,81 €	155
14	MONDELEZ INTERNATIONAL	COLL DE LA MANYA	110	50000000	7005	977071,41	8011	23.054.000,00 €	21.528,54 €	8.163,86 €	29.692,41 €	195,71 €	143
15	PIERRE FABRE	COLL DE LA MANYA	35	124974000	10870	19124748,6	7590	32.343.000,00 €	33.377,96 €	7.735,03 €	41.112,99 €	953,66 €	150,7
16	MENZOLIT VITROPLAST	COLL DE LA MANYA	32	15237000	3262	935433,954	4880	2.405.858,70 €	10.053,16 €	4.974,63 €	15.027,79 €	314,16 €	170,8
17	INDUSTRIAS PLASTICAS PUIG	COLL DE LA MANYA	18	3090000	1500	430150,5	2260	944.265,48 €	4.651,18 €	2.305,90 €	6.957,07 €	258,40 €	166
18	SOLAR STEM	COLL DE LA MANYA	7	1562000	890	250718,17	620	43.260,62 €	2.781,02 €	612,95 €	3.393,97 €	397,29 €	154
19	EXAL - EXTRUIDOS DEL ALUMINIO S.A. (ALUMINERA)	FONT DEL RADIUM	50	6000000	7330	6246194,69	3670	1.213.042,00 €	22.524,94 €	3.742,12 €	26.267,06 €	450,50 €	150,1
20	RELEM	COLL DE LA MANYA	25	4031000	1710	802184,965	2110	1.062.512,86 €	5.295,00 €	2.153,11 €	7.448,11 €	211,80 €	144
21	CINTACOR SA	COLL DE LA MANYA	30	4617000	2795	0	3180	1.121.349,34 €	8.621,42 €	3.243,01 €	11.864,43 €	287,38 €	164
22	HAARSLEV	FONT DEL RADIUM	100	34152000	1700	499381,542	1400	5.821.871,00 €	5.264,34 €	1.429,90 €	6.694,24 €	52,64 €	160,6
23	GERCO	FONT DEL RADIUM	11	1181000	965	0	20	527.739,52 €	3.010,96 €	23,51 €	3.034,47 €	273,72 €	161
24	COIMBRA	FONT DEL RADIUM	12	1475000	560	204400	1100	386.607,97 €	1.769,30 €	1.124,32 €	2.893,62 €	147,44 €	162
25	HOSPITALITY,SL	FONT DEL RADIUM	13	1867000	665	0	3690	879.851,85 €	2.091,21 €	3.762,49 €	5.853,71 €	160,86 €	180
26	MONTSEC	FONT DEL RADIUM	13	8307000	660	433357,32	710	520.923,26 €	2.075,88 €	701,36 €	2.777,25 €	159,68 €	162
27	COALIMENT GRANOLLERS S.A.	FONT DEL RADIUM	270	164857000	18657	0	21320	8.307.222,00 €	57.251,53 €	21.720,41 €	78.971,95 €	212,04 €	147,7
28	KINGPACK SL	COLL DE LA MANYA	43	2158000	4765	0	4800	982.591,04 €	14.661,09 €	4.893,14 €	19.554,23 €	340,96 €	172
29	VERTISOL INTERNACIONAL, SRL	COLL DE LA MANYA	75	18000000	15813	33227920,2	570	3.924.092,09 €	48.532,33 €	563,83 €	49.096,16 €	647,10 €	125,2
30	PINTADOS TECNICOS DEL VALLES, SL	COLL DE LA MANYA	9	1017000	619	113277	2140	551.606,95 €	1.950,18 €	2.183,66 €	4.133,85 €	216,69 €	135,9
31	AIRNOU SL	COLL DE LA MANYA	19	1250000	1410	0	890	1.043.727,44 €	4.375,25 €	910,41 €	5.285,67 €	230,28 €	141,3
32	AUTOMÒBILS BERTRAN	FONT DEL RADIUM	50	22694000	8042	0	7450	2.557.898,15 €	24.707,80 €	7.592,43 €	32.300,23 €	494,16 €	147,3
33	PAVER, SL	COLL DE LA MANYA	92	19623000	5429	0	8120	2.319.845,39 €	16.696,80 €	8.274,89 €	24.971,69 €	181,49 €	144
34	SERVICIOS INDUSTRIALES REUNIDOS SA	FONT DEL RADIUM	350	10233000	701	0	1810	14.788.042,54 €	2.201,58 €	1.847,53 €	4.049,11 €	6,29 €	160,5
35	BUSCH IBERICA, SA	COLL DE LA MANYA	32	9096000	3922	0	13260	3.121.851,43 €	12.076,60 €	13.510,50 €	25.587,10 €	377,39 €	171,1
36	RIERA NADEU, SA	COLL DE LA MANYA	37	6257000	4775	336494,25	6600	2.984.501,91 €	14.691,75 €	6.726,62 €	21.418,37 €	397,07 €	168,1
37	MARABU ESPAÑA	COLL DE LA MANYA	10	2185000	1620	429797,504	430	342.474,00 €	5.019,07 €	426,29 €	5.445,37 €	501,91 €	163,5
38	MAQUINSER SA	COLL DE LA MANYA	8	12240000	1266	0	1190	770.046,97 €	3.933,77 €	1.215,99 €	5.149,77 €	491,72 €	159

39	DUBOSA DEL VALLES, SL	FONT DEL RADIUM	9	1191000	783	0	500	287.185,41 €	2.452,98 €	495,06 €	2.948,04 €	272,55 €	158,3
40	TTS	COLL DE LA MANYA	7	1867000	1258	0	320	373.677,25 €	3.909,25 €	318,23 €	4.227,47 €	558,46 €	161
41	SALICE ESPAÑA, SL	COLL DE LA MANYA	8	3703000	1439	0	2700	513.432,63 €	4.464,16 €	2.754,08 €	7.218,24 €	558,02 €	154,5
42	MATIC	COLL DE LA MANYA	12	7276000	2342	165040,74	1140	631.503,97 €	7.232,60 €	1.165,06 €	8.397,66 €	602,72 €	160
43	TORVISCO	FONT DEL RADIUM	12	1974000	4393	0	1620	463.728,89 €	13.520,61 €	1.653,99 €	15.174,60 €	1.126,72 €	196,7
44	ART DAMILIA	FONT DEL RADIUM	10	1157000	540	0	600	186.374,03 €	1.707,98 €	593,30 €	2.301,28 €	170,80 €	180
45	GROUPE LOGISTICS- IDL ESPAÑA, SLU	FONT DEL RADIUM	50	100000000	5637	0	4460	25.392.310,00 €	17.334,49 €	4.546,82 €	21.881,31 €	346,69 €	161,7
46	SEBASTIA LLORENS	FONT DEL RADIUM	50	80000000	5121	0	14100	3.205.074,07 €	15.752,53 €	14.366,12 €	30.118,65 €	315,05 €	147,7
47	MAQUINARIA INDUSTRIAL DARA	COLL DE LA MANYA	72	9366000	5467	385259,49	3430	7.494.245,25 €	16.813,30 €	3.497,66 €	20.310,96 €	233,52 €	144
48	TALLERS JOBO TRUCK	FONT DEL RADIUM	5	1000000	753	0	560	78.279,80 €	2.361,00 €	554,00 €	2.915,01 €	472,20 €	151,2
49	BOXMOTIONS	COLL DE LA MANYA	5	2000000	2538	0	3620	132.917,66 €	7.833,50 €	3.691,19 €	11.524,69 €	1.566,70 €	170,6
50	SEBASTIA LLORENS, SL	COLL DE LA MANYA	50	80000000	642	0	2450	3.205.074,07 €	2.020,70 €	2.499,43 €	4.520,13 €	40,41 €	159

Table C.1: *Companies global information*

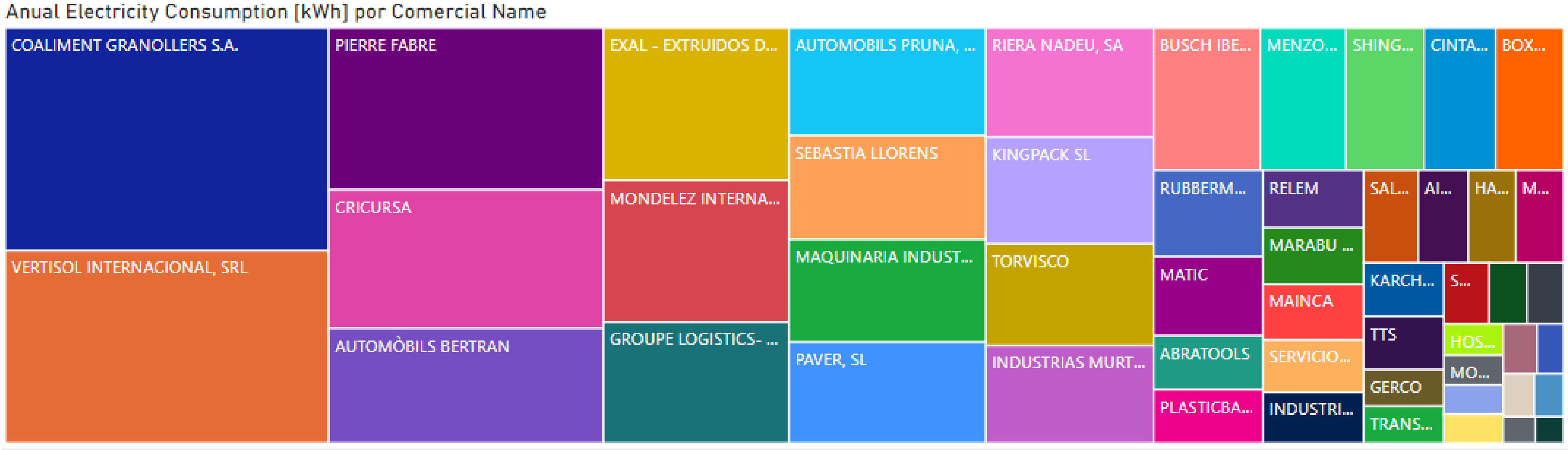


Figure C.1: *Annual Electricity Consumption of observations (companies) for Statistical Study.*

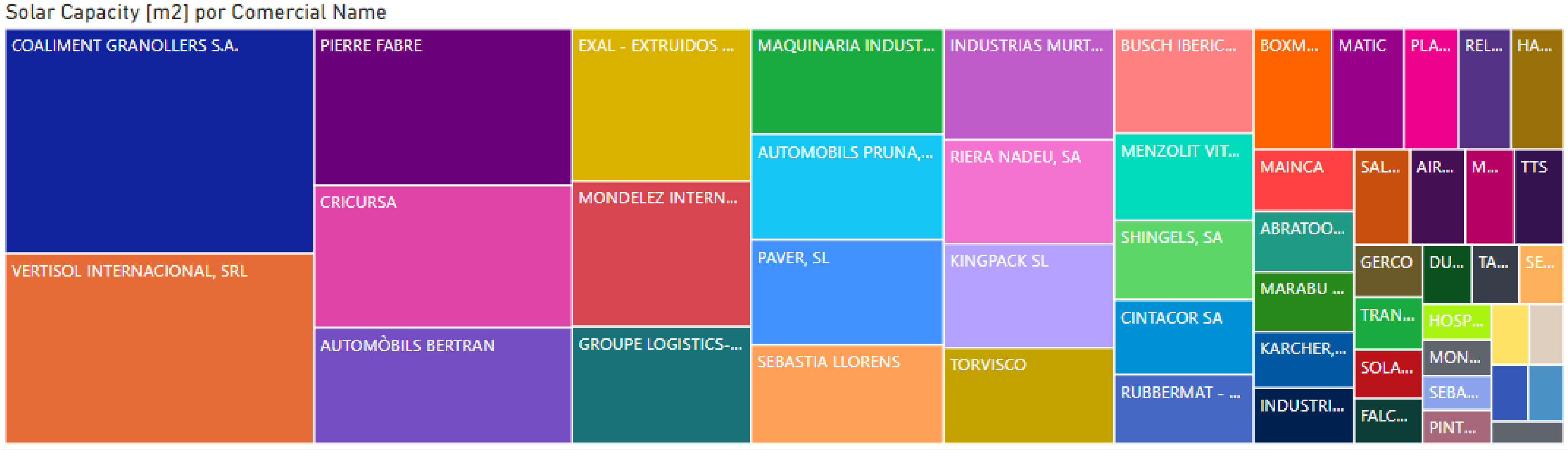


Figure C.6.1: *Solar Capacity of observations (companies) for Statistical Study.*

Information of companies located in the conglomerate 3 based on sub-section 5.3.3 and the clustering of observations:

ID04 - TRANSPORTES JUBERA: Company specialized in removals and special transport of new furniture by road. It has about 15 workers on staff and has an area of 964 m^2 of industrial building.

ID09 – MAINCA: Manufacture and marketing of machinery for the meat industry. It has 27 workers and a total area of 1674 m^2.

ID30 – PINTADOS TECNICOS DEL VALLES: S It is specialized in the coating of powder and liquid metal parts. It has 9 workers and 619 m^2.

ID31 – AIRNOU S.L: Company specialized in the air conditioning of all kinds of spaces, has 19 workers and 1410 m^2 of surface.

ID20 – RELEM: They are solely and exclusively dedicated to the manufacture of tubes. They have 25 workers and an industrial building of 1710 m^2.

ID33 – PAVER S.L: Stamping, cold drawing and die construction. They have 92 employees and large industrial buildings of 5429 m^2.

ID17 – INDUSTRIAS PLASTICAS PUIG: Industry dedicated to the manufacture of plastic packaging for the pharmaceutical sector. It has 18 workers and an industrial building of 1500 m^2.

ID23 – GERCO: Authorised management centre for dangerous and non-dangerous waste. It has 11 employees on staff and a 965 m^2.

ID39 – DUBOSA: They sell moulds, cans and coatings for the bakery industry. They have 9 workers and 783 m^2 of industrial building.

ID27 – COALIMENT GRANOLLERS: large company dedicated to the wholesale trade of cosmetics, drugstore and food products. They have 270 employees and some of the largest industrial buildings on the estate (18657m^2).

ID47 – MAQUINARIA DARA: Manufacture of packaging machinery for the pharmaceutical, veterinary and cosmetic industry. They have 72 workers and 5467 m^2 of industrial building.

Appendix D

D Statistical approach

D.1 Linear Regression - Applied Methodology

A linear regression model will be used to find the function that use the variables on which the electricity and water consumption of the factories of an industrial area depends.

The model will be estimated using clustered data and the following alternative methodology based on a multiple linear regression, created by the authors: Hsiao (1989), Gujarati (1992) and Wooldridge (2009).

1) Multiple linear regression model: considering 'k' as explanatory variables, the regression equation will assume the following form.

$$Y_{it} = \beta_0 + \beta_1 x_{1it} + \beta_2 x_{2it} + \beta_3 x_{3it} + \cdots + \beta_k x_{kit} + u_{it} \quad como \ \begin{Bmatrix} i = 1,2,3, \dots , n \\ t = 1,2,3, \dots , T \end{Bmatrix} \qquad \text{(D.1)}$$

Where,

β_0	-	Separate term
β_j	-	Unknown regression coefficients, such as j = 1, …, k
x_{jit}	-	Explanatory variables, such as j = 1, …, k
u_{it}	-	Error term

Developing this expression, a system of "n" equations is obtained that can be grouped and represented in the following matrix form:

$$\begin{pmatrix} y_{1t} \\ y_{2t} \\ \vdots \\ y_{nt} \end{pmatrix} = \begin{pmatrix} 1 & x_{11t} & x_{21t} & x_{31t} & \cdots & x_{k1t} \\ 1 & x_{12t} & x_{22t} & x_{32t} & \cdots & x_{k2t} \\ \vdots & \vdots & \vdots & \vdots & & \vdots \\ 1 & x_{1nt} & x_{2nt} & x_{3nt} & \cdots & x_{knt} \end{pmatrix} \begin{pmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_k \end{pmatrix} + \begin{pmatrix} u_{1t} \\ u_{2t} \\ \vdots \\ u_{nt} \end{pmatrix}$$

$$\boldsymbol{Y_t} = \boldsymbol{X_t \beta} + \boldsymbol{u_t} \qquad (t = 1, \dots , T) \qquad \text{(D.2)}$$

To estimate the coefficients β_j, it is necessary to assume that both the intersection and the coefficients are constant with respect to time. In this way, the term error is assumed to be the differences between individuals and differences across time periods, being the method to use the **Ordinary Least Squares (OLS).**

2) Ordinary Minimum Square Method: This method is based on minimising the sum of squares of random residues or disturbances, i.e. minimising the difference between the y_{it} real function and its estimated value $\hat{y}_{it}$. The idea is to minimize error e_{it} through equation D.3.

$$Min\sum_{i=1}^{n}\sum_{t=1}^{m}e_{it}^{2}=\sum_{i=1}^{n}\sum_{t=1}^{m}(y_{it}-\hat{y}_{it})^{2}$$

(D.3)

Deriving partially this equation, in order to each of the coefficients β_j, a system of normal equations will be obtained that will be expressed in matrix form as follows:

$$\begin{pmatrix} 1 & 1 & \cdots & 1 \\ x_{11t} & x_{12t} & \cdots & x_{1nt} \\ x_{21t} & x_{22t} & \cdots & x_{2nt} \\ x_{31t} & x_{32t} & \cdots & x_{3nt} \\ \vdots & \vdots & & \vdots \\ x_{k1t} & x_{k2t} & \cdots & x_{knt} \end{pmatrix} \begin{pmatrix} 1 & x_{11t} & x_{21t} & x_{31t} & \cdots & x_{k1t} \\ 1 & x_{12t} & x_{22t} & x_{32t} & \cdots & x_{k2t} \\ \vdots & \vdots & \vdots & \vdots & & \vdots \\ 1 & x_{1nt} & x_{2nt} & x_{3nt} & \cdots & x_{knt} \end{pmatrix} \begin{pmatrix} \widehat{\beta_0} \\ \widehat{\beta_1} \\ \vdots \\ \widehat{\beta_k} \end{pmatrix} = \begin{pmatrix} 1 & 1 & \cdots & 1 \\ x_{11t} & x_{12t} & \cdots & x_{1nt} \\ x_{21t} & x_{22t} & \cdots & x_{2nt} \\ x_{31t} & x_{32t} & \cdots & x_{3nt} \\ \vdots & \vdots & & \vdots \\ x_{k1t} & x_{k2t} & \cdots & x_{knt} \end{pmatrix} \begin{pmatrix} y_{1t} \\ y_{2t} \\ \vdots \\ y_{nt} \end{pmatrix}$$

$$\boldsymbol{X'X\widehat{\beta}} = \boldsymbol{X'Y_t} \qquad \text{(D.4)}$$

Multiplying each member by $(\boldsymbol{X'X})^{-1}$, will result in each of the estimators β_j, so:

$$\widehat{\boldsymbol{\beta_{OLS}}} = (\boldsymbol{X'X})^{-1}\boldsymbol{X'Y_t} \qquad \text{(D.5)}$$

3) Model validation and determination coefficient: After estimating the regression parameters, it is necessary to perform an analysis that allows us to diagnose what magnitude of the total variability is explained by the model, performing the following hypothesis test for it.

$$H_0: Correct\ model\ \rightarrow \beta_1 = \beta_2 = \cdots = \beta_j = 0$$

$$H_1:\ H_0\ is\ False \rightarrow if\ one\ \beta_j \neq 0$$

The **F-Snedecor** distribution test is applied to perform this validation and it is necessary to carry out the global significance contrast by comparing the variables of the experimental statistic (F_c) and the theoretical statistic (F_{tab}). The experimental value is calculated by means of the following equation D.6:

$$F_c = \frac{\frac{R^2}{k-1}}{\frac{(1-R^2)}{n-k}} \qquad \text{(D.6)}$$

Where R^2 is the determination coefficient obtained in the equation D.7, k is the number of equations used and n is the number of dependent variables.

The decision rule will reject the null hypothesis (H_0) if $F_c > F_{tab}$ where F_{tab} is obtained from the **F** distribution table with k degrees of freedom in the numerator, $n-(k+1)$ in the denominator and taking into account a significance level (1-α) (normally is used 95%).

The determination coefficient R^2 indicates the proportion of the total variability of the dependent variable that is explained by the estimated model, and its calculation formula is:

$$R^2 = \frac{\sum_{i=1}^{n}(\hat{y}_{it}-\overline{y_{it}})^2}{\sum_{i=1}^{n}(\overline{y_{it}}-y_{it})^2} \tag{D.7}$$

This coefficient varies between 0 and 1, and the closest to 1, more accurate the model will be.

4) Validation of parameter assumptions: The following is the stage of statistical validation of the regression parameters, i.e. whether they are significant or not by applying in this case the **t-Student** significance test to the regression coefficients.

A significance test is a procedure by which the sample results are used to verify the truth or falsity of a hypothesis, and the test being performed:

$$H_0: \beta_j = 0 \qquad for\ j = 1, \dots, k$$

$$H_1: \beta_j \neq 0 \qquad for\ j = 1, \dots, k$$

In case the null hypothesis ($\boldsymbol{H_0}$) is rejected, it is admitted that the variable associated with the respective coefficient β_j is significant, i.e. it has explanatory power on the dependent variable.

To admit the hypothesis of normality $\widehat{\beta_j}$, it is necessary to compare the experimental statistic (t_c) with the theoretical one (t_{tab}) for a **t-Student** distribution:

$$t_c \sim t_{tab} \rightarrow \frac{\widehat{\beta_j}-\beta_j}{se(\widehat{\beta_j})} \sim t_{n-k-1} \tag{D.8}$$

Where $\widehat{\beta_j}$ is the estimated standard deviation of the parameter β_j, $se(\widehat{\beta_j})$ the real standard deviation ,β_j the parameter estimator, k the number of equations used and n is the number of dependent variables.

The decision rule will reject the null hypothesis (H_0) when the absolute value of $\left|\frac{\widehat{\beta_j}-\beta_j}{se(\widehat{\beta_j})}\right|^2$ will be greater than $t_{\frac{\alpha}{2}}$, i.e, the value found from the t-Student distribution table with a probability $\boldsymbol{\frac{\alpha}{2}}$, where alpha is the significance level. This will also verify whenever the probability that $\boldsymbol{P\left(t_{(n-k-1)} > t_{\frac{\alpha}{2}}\right)}$ will be equal to $\boldsymbol{\frac{\alpha}{2}}$, with normally a 5% significance level.

5) Selection criteria: To facilitate the choice of model, the following indicators are considered.

$$AIC = -2\ log\left(\frac{SQR}{n}\right) + \frac{2k}{n} \rightarrow Akaike\ Information\ Criterion \tag{D.9}$$

$$SIC = -2\ log\left(\frac{SQR}{n}\right) + \frac{k \log n}{n} \rightarrow Schwarz\ Information\ Criterion \tag{D.10}$$

$$\boldsymbol{SQR}\ is\ the\ sum\ of\ the\ squares\ of\ the\ waste$$

Using these two criteria, the models are selected for the respective sensitivity analysis and they estimate the relative amount of information lost by a given model: the less information a model loses, the higher the quality of that model. In estimating the amount of information lost by a model, these parameters deal with the trade-off between the goodness of fit of the model and the simplicity of the model. In other words, the models with the lowest values for these two criteria will be the ones who will lose the least information and will have to be chosen.

D.2 Linear Regression – Results analysis

In this section, the different models prepared to analyse electricity and water consumption will be presented and analysed.

The reason that led to the development of several models was to avoid the presence of multicollinearity since the variables "dimensional factors" are highly correlated between them. The covariance of the variables is studied using the Minitab software in the previous chapter "Treatment of the variables".

In the case of correlations less than 90%, it is decided to include them in the model since they could create multicollinearity, i. e., the model could be accepted, however, the estimators would not be efficient. In this case, the size of the building is not directly related to the turnover, the number of workers or the thermal consumption of the company. In the case of the relationship between the number of workers (**n_work**) and annual hours worked per worker (**hor_work**) it is decided to remove the latter by maximum correlation, equal to 1.

To analyze the results, the respective estimated coefficients β_j, the standard deviation $\boldsymbol{\sigma^2}$ and the $\boldsymbol{p}$ value have been determinated. The estimated coefficients measure the impact of a variation in the respective explanatory variable on the dependent variable, while the standard deviation indicates the variation of each estimated coefficient in relation to its mean value, while the $\boldsymbol{p}$ value indicates the level of significance of the respective coefficient, where a $\boldsymbol{p}$ value below 5% translates into a greater probability of accepting a relationship between the explanatory variable and the dependent variable.

Another important point to mention is that for the analysis of impacts on consumption, when reference is made to a given variable, the rest are considered constant. To determine the model that best explains the variations and allocations in electricity and water consumption in relation to the explanatory variables, four models were constructed. The choice of the best model led to the comparison of the coefficients of determination R^2 of each one, selecting the one with the highest coefficient. In addition, the values of the respective selection criteria of AIC and SIC were also compared, always choosing the one with the lowest value.

Regressive multicollinearity is a condition that occurs when some predictor variables included in the model are correlated with other predictor variables. Severe multicollinearity is problematic because it can increase the variance of regression coefficients, making them unstable. To measure multicollinearity, variance inflation factors (FIV) are used. If all FIVs are 1, there is no multicollinearity, but if some FIVs are greater than 1, the predictors are correlated. When an FIV is > 5, the regression coefficient for that term is not adequately estimated. In this case, only the latter condition has been taken into consideration because all the models analysed are between the value of FIV 1 and 3.

The standard deviation of an estimate (**EE of Coefficient**) is called the standard error. The standard error of the coefficient measures the precision with which the model estimates the unknown value of the coefficient. This is used to measure the precision of the estimate of the coefficient. The smaller the standard error, the more accurate the estimation.

The different models analysed consist of the same variables chosen in the section Treatment of Variables, but each one varies according to whether each of these variables has a data adjustment using decimal logarithms. These are called double logarithmic models and their theoretical expression would be as follows:

$$\log(Y_{it}) = \beta_0 + \beta_1 \log(x_{1it}) + \beta_2 \log(x_{2it}) + \cdots + \beta_k \log(x_{kit}) + u_{it} \qquad \text{(D.11)}$$

Adjusting the variables with decimal logarithms allows to model situations in which variations of % in dependent variables x_{kit} , produce variations of constant % in independent variable Y_{it}, i.e, with constant elasticity. In addition, it helps a lot in this section because they are very useful in studies of demand, production, costs, etc. Below, the models elaborated together with the respective analysis of the results are attached.

D.3 Akaike Information Criterion

The Akaike information criterion (AIC) is an estimator of out-of-sample prediction error and thereby relative quality of statistical models for a given set of data. Given a collection of models for the data, AIC estimates the quality of each model, relative to each of the other models. Thus, AIC provides a means for model selection.

AIC is founded on information theory. When a statistical model is used to represent the process that generated the data, the representation will almost never be exact; so some information will be lost by using the model to represent the process. AIC estimates the relative amount of information lost by a given model: the less information a model loses, the higher the quality of that model.

In estimating the amount of information lost by a model, AIC deals with the trade-off between the goodness of fit of the model and the simplicity of the model. In other words, AIC deals with both the risk of overfitting and the risk of under fitting.

The Akaike information criterion is named after the Japanese statistician Hirotugu Akaike, who formulated it. It now forms the basis of a paradigm for the foundations of statistics; as well, it is widely used for statistical inference.

D.4 Schwarz Information Criterion

In statistics, the Bayesian information criterion (BIC) or Schwarz information criterion (also SIC, SBC, SBIC) is a criterion for model selection among a finite set of models; the model with the lowest BIC is preferred. It is based, in part, on the likelihood function and it is closely related to the Akaike information criterion (AIC).

When fitting models, it is possible to increase the likelihood by adding parameters, but doing so may result in overfitting. Both BIC and AIC attempt to resolve this problem by introducing a penalty term for the number of parameters in the model; the penalty term is larger in BIC than in AIC. The BIC was developed by Gideon E. Schwarz and published in a 1978 paper, where he gave a Bayesian argument for adopting it.

D.5 F-Snedecor Tables

For the problem, it shown the value with degrees of freedom in the denominator $(n-k+1)$,degrees of freedom in the numerator k and probability (p) equal to α.

Degrees of freedom in the denominator → $(n-k+1) = \big((50\cdot 4)-50+1\big) = 151$

Degrees of freedom in the denominator → $k = 50$

Probability → $\alpha = 0.05$

TABLE E

F critical values (continued)

Degrees of freedom in the denominator		Degrees of freedom in the numerator								
	p	1	2	3	4	5	6	7	8	9
28	.100	2.89	2.50	2.29	2.16	2.06	2.00	1.94	1.90	1.87
	.050	4.20	3.34	2.95	2.71	2.56	2.45	2.36	2.29	2.24
	.025	5.61	4.22	3.63	3.29	3.06	2.90	2.78	2.69	2.61
	.010	7.64	5.45	4.57	4.07	3.75	3.53	3.36	3.23	3.12
	.001	13.50	8.93	7.19	6.25	5.66	5.24	4.93	4.69	4.50
29	.100	2.89	2.50	2.28	2.15	2.06	1.99	1.93	1.89	1.86
	.050	4.18	3.33	2.93	2.70	2.55	2.43	2.35	2.28	2.22
	.025	5.59	4.20	3.61	3.27	3.04	2.88	2.76	2.67	2.59
	.010	7.60	5.42	4.54	4.04	3.73	3.50	3.33	3.20	3.09
	.001	13.39	8.85	7.12	6.19	5.59	5.18	4.87	4.64	4.45
30	.100	2.88	2.49	2.28	2.14	2.05	1.98	1.93	1.88	1.85
	.050	4.17	3.32	2.92	2.69	2.53	2.42	2.33	2.27	2.21
	.025	5.57	4.18	3.59	3.25	3.03	2.87	2.75	2.65	2.57
	.010	7.56	5.39	4.51	4.02	3.70	3.47	3.30	3.17	3.07
	.001	13.29	8.77	7.05	6.12	5.53	5.12	4.82	4.58	4.39
40	.100	2.84	2.44	2.23	2.09	2.00	1.93	1.87	1.83	1.79
	.050	4.08	3.23	2.84	2.61	2.45	2.34	2.25	2.18	2.12
	.025	5.42	4.05	3.46	3.13	2.90	2.74	2.62	2.53	2.45
	.010	7.31	5.18	4.31	3.83	3.51	3.29	3.12	2.99	2.89
	.001	12.61	8.25	6.59	5.70	5.13	4.73	4.44	4.21	4.02
50	.100	2.81	2.41	2.20	2.06	1.97	1.90	1.84	1.80	1.76
	.050	4.03	3.18	2.79	2.56	2.40	2.29	2.20	2.13	2.07
	.025	5.34	3.97	3.39	3.05	2.83	2.67	2.55	2.46	2.38
	.010	7.17	5.06	4.20	3.72	3.41	3.19	3.02	2.89	2.78
	.001	12.22	7.96	6.34	5.46	4.90	4.51	4.22	4.00	3.82
60	.100	2.79	2.39	2.18	2.04	1.95	1.87	1.82	1.77	1.74
	.050	4.00	3.15	2.76	2.53	2.37	2.25	2.17	2.10	2.04
	.025	5.29	3.93	3.34	3.01	2.79	2.63	2.51	2.41	2.33
	.010	7.08	4.98	4.13	3.65	3.34	3.12	2.95	2.82	2.72
	.001	11.97	7.77	6.17	5.31	4.76	4.37	4.09	3.86	3.69
100	.100	2.76	2.36	2.14	2.00	1.91	1.83	1.78	1.73	1.69
	.050	3.94	3.09	2.70	2.46	2.31	2.19	2.10	2.03	1.97
	.025	5.18	3.83	3.25	2.92	2.70	2.54	2.42	2.32	2.24
	.010	6.90	4.82	3.98	3.51	3.21	2.99	2.82	2.69	2.59
	.001	11.50	7.41	5.86	5.02	4.48	4.11	3.83	3.61	3.44
200	.100	2.73	2.33	2.11	1.97	1.88	1.80	1.75	1.70	1.66
	.050	3.89	3.04	2.65	2.42	2.26	2.14	2.06	1.98	1.93
	.025	5.10	3.76	3.18	2.85	2.63	2.47	2.35	2.26	2.18
	.010	6.76	4.71	3.88	3.41	3.11	2.89	2.73	2.60	2.50
	.001	11.15	7.15	5.63	4.81	4.29	3.92	3.65	3.43	3.26
1000	.100	2.71	2.31	2.09	1.95	1.85	1.78	1.72	1.68	1.64
	.050	3.85	3.00	2.61	2.38	2.22	2.11	2.02	1.95	1.89
	.025	5.04	3.70	3.13	2.80	2.58	2.42	2.30	2.20	2.13
	.010	6.66	4.63	3.80	3.34	3.04	2.82	2.66	2.53	2.43
	.001	10.89	6.96	5.46	4.65	4.14	3.78	3.51	3.30	3.13

Table D.1: *F-Snedecor critical values table (Part 1).*

TABLE E

F critical values (continued)

Degrees of freedom in the numerator										
10	12	15	20	25	30	40	50	60	120	1000
1.84	1.79	1.74	1.69	1.65	1.63	1.59	1.57	1.56	1.52	1.48
2.19	2.12	2.04	1.96	1.91	1.87	1.82	1.79	1.77	1.71	1.66
2.55	2.45	2.34	2.23	2.16	2.11	2.05	2.01	1.98	1.91	1.84
3.03	2.90	2.75	2.60	2.51	2.44	2.35	2.30	2.26	2.17	2.08
4.35	4.11	3.86	3.60	3.43	3.32	3.18	3.09	3.02	2.86	2.72
1.83	1.78	1.73	1.68	1.64	1.62	1.58	1.56	1.55	1.51	1.47
2.18	2.10	2.03	1.94	1.89	1.85	1.81	1.77	1.75	1.70	1.65
2.53	2.43	2.32	2.21	2.14	2.09	2.03	1.99	1.96	1.89	1.82
3.00	2.87	2.73	2.57	2.48	2.41	2.33	2.27	2.23	2.14	2.05
4.29	4.05	3.80	3.54	3.38	3.27	3.12	3.03	2.97	2.81	2.66
1.82	1.77	1.72	1.67	1.63	1.61	1.57	1.55	1.54	1.50	1.46
2.16	2.09	2.01	1.93	1.88	1.84	1.79	1.76	1.74	1.68	1.63
2.51	2.41	2.31	2.20	2.12	2.07	2.01	1.97	1.94	1.87	1.80
2.98	2.84	2.70	2.55	2.45	2.39	2.30	2.25	2.21	2.11	2.02
4.24	4.00	3.75	3.49	3.33	3.22	3.07	2.98	2.92	2.76	2.61
1.76	1.71	1.66	1.61	1.57	1.54	1.51	1.48	1.47	1.42	1.38
2.08	2.00	1.92	1.84	1.78	1.74	1.69	1.66	1.64	1.58	1.52
2.39	2.29	2.18	2.07	1.99	1.94	1.88	1.83	1.80	1.72	1.65
2.80	2.66	2.52	2.37	2.27	2.20	2.11	2.06	2.02	1.92	1.82
3.87	3.64	3.40	3.14	2.98	2.87	2.73	2.64	2.57	2.41	2.25
1.73	1.68	1.63	1.57	1.53	1.50	1.46	1.44	1.42	1.38	1.33
2.03	1.95	1.87	1.78	1.73	1.69	1.63	1.60	1.58	1.51	1.45
2.32	2.22	2.11	1.99	1.92	1.87	1.80	1.75	1.72	1.64	1.56
2.70	2.56	2.42	2.27	2.17	2.10	2.01	1.95	1.91	1.80	1.70
3.67	3.44	3.20	2.95	2.79	2.68	2.53	2.44	2.38	2.21	2.05
1.71	1.66	1.60	1.54	1.50	1.48	1.44	1.41	1.40	1.35	1.30
1.99	1.92	1.84	1.75	1.69	1.65	1.59	1.56	1.53	1.47	1.40
2.27	2.17	2.06	1.94	1.87	1.82	1.74	1.70	1.67	1.58	1.49
2.63	2.50	2.35	2.20	2.10	2.03	1.94	1.88	1.84	1.73	1.62
3.54	3.32	3.08	2.83	2.67	2.55	2.41	2.32	2.25	2.08	1.92
1.66	1.61	1.56	1.49	1.45	1.42	1.38	1.35	1.34	1.28	1.22
1.93	1.85	1.77	1.68	1.62	1.57	1.52	1.48	1.45	1.38	1.30
2.18	2.08	1.97	1.85	1.77	1.71	1.64	1.59	1.56	1.46	1.36
2.50	2.37	2.22	2.07	1.97	1.89	1.80	1.74	1.69	1.57	1.45
3.30	3.07	2.84	2.59	2.43	2.32	2.17	2.08	2.01	1.83	1.64
1.63	1.58	1.52	1.46	1.41	1.38	1.34	1.31	1.29	1.23	1.16
1.88	1.80	1.72	1.62	1.56	1.52	1.46	1.41	1.39	1.30	1.21
2.11	2.01	1.90	1.78	1.70	1.64	1.56	1.51	1.47	1.37	1.25
2.41	2.27	2.13	1.97	1.87	1.79	1.69	1.63	1.58	1.45	1.30
3.12	2.90	2.67	2.42	2.26	2.15	2.00	1.90	1.83	1.64	1.43
1.61	1.55	1.49	1.43	1.38	1.35	1.30	1.27	1.25	1.18	1.08
1.84	1.76	1.68	1.58	1.52	1.47	1.41	1.36	1.33	1.24	1.11
2.06	1.96	1.85	1.72	1.64	1.58	1.50	1.45	1.41	1.29	1.13
2.34	2.20	2.06	1.90	1.79	1.72	1.61	1.54	1.50	1.35	1.16
2.99	2.77	2.54	2.30	2.14	2.02	1.87	1.77	1.69	1.49	1.22

***Table D.2:** F-Snedecor critical values table (Part 2).*

D.6 Water Consumption Model

Results of the water consumption models developed with software Minitab. Related to section 4.3.2.

$$\log(\text{Cons\_H2O}) = 0{,}857 + 0{,}489\log(\text{M\_2}) + 0{,}174\log(\text{n\_work}) + 0{,}167\log(\text{turn}) - 0{,}112\log(\text{Cons\_Term})$$

Term	Coef	EE del coef.	Value T	Value p	FIV
Constante	0,857	0,542	1,58	0,121	
log(M_2)	0,489	0,174	2,81	0,007	1,46
log(turn)	0,167	0,146	1,14	0,258	2,44
log(n_work)	0,174	0,209	0,83	0,408	2,46
Cons_Term	-0,112	0,123	-0,91	0,368	1,01

S	R-sq.	R-sq. (adjusted)	R-sq. (pred)
0,431612	40,84%	35,59%	28,98%

Table D.3: *Model 1 of water consumption.*

$$\log(\text{Cons\_H2O}) = 0{,}681 + 0{,}523\log(\text{M\_2}) + 0{,}248\log(\text{turn}) - 0{,}109\,\text{Cons\_Term}$$

Term	Coef	EE del coef.	Value T	Value p	FIV
Constante	0,681	0,534	1,28	0,208	
log(M_2)	0,523	0,171	3,06	0,004	1,38
log(turn)	0,248	0,128	1,94	0,058	1,85
n_work	-0,00002	0,00109	-0,01	0,988	1,47
Cons_Term	-0,109	0,125	-0,87	0,387	1,02

S	R-sq.	R-sq. (adjusted)	R-sq. (pred)
0,434940	39,93%	34,59%	27,27%

Table D.4: *Model 2 of water consumption.*

$$\log(\text{Cons\_H2O}) = 1{,}244 + 0{,}613\log(\text{M\_2}) + 0{,}00057\,\text{n\_work} + 0{,}000002\,\text{turn} - 0{,}081\,\text{Cons\_Term}$$

Term	Coef	EE del coef.	Value T	Value p	FIV
Constante	1,244	0,534	2,33	0,024	
log(M_2)	0,613	0,166	3,68	0,001	1,24
turn	0,000002	0,000002	1,06	0,293	1,52
n_work	0,00057	0,00107	0,53	0,596	1,33
Cons_Term	-0,081	0,129	-0,63	0,531	1,03

S	R-sq.	R-sq. (adjusted)	R-sq. (pred)
0,447252	36,48%	30,83%	23,97%

Table D.5: *Model 3 of water consumption.*

$$\log(\text{Cons\_H2O}) = 2{,}658 + 0{,}000036\,\text{M\_2} + 0{,}388\log(\text{n\_work}) + 0{,}000001\,\text{turn} - 0{,}084\,\text{Cons\_Term}$$

Término	Coef	EE del coef.	Valor T	Valor p	FIV
Constante	2,658	0,240	11,07	0,000	
M_2	0,000036	0,000022	1,66	0,103	1,57
turn	0,000001	0,000002	0,42	0,673	1,72
log(n_work)	0,388	0,184	2,11	0,040	1,66
Cons_Term	-0,084	0,133	-0,63	0,533	1,03

S	R-sq.	R-sq. (adjusted)	R-sq. (pred)
0,462655	32,03%	25,99%	9,09%

Table D.6: *Model 4 of water consumption.*

Comparation between model **Cons_H2O** with **Log(Cons_H2O)**:

Cons_H2O = 1867 + 0,649 M_2 + 3,79 n_work + 0,0204 turn - 1942 Cons_Term

Term	Coef	EE del coef.	IC de 95%	Value T	Value p	FIV
Constante	1867	777	(301; 3433)	2,40	0,021	
M_2	0,649	0,145	(0,356; 0,941)	4,47	0,000	1,46
n_work	3,79	7,77	(-11,86; 19,44)	0,49	0,628	1,36
turn	0,0204	0,0162	(-0,0121; 0,0529)	1,26	0,213	1,65
Cons_Term	-1942	922	(-3799; -85)	-2,11	0,041	1,02

S	R-sq.	R-sq. (adjusted)	PRESS	R-sq. (pred)	AICc	BIC
3210,11	52,53%	48,31%	730862070	25,18%	957,99	967,50

Table D.7: *Equation of regression – Cons_H2O.*

log(Cons_H2O) = 0,857 + 0,489 log(M_2) + 0,167 log(turn) + 0,174 log(n_work) - 0,112 Cons_Term

Term	Coef	EE del coef.	IC de 95%	Value T	Value p	FIV
Constante	0,857	0,542	(-0,235; 1,949)	1,58	0,121	
log(M_2)	0,489	0,174	(0,138; 0,839)	2,81	0,007	1,46
log(turn)	0,167	0,146	(-0,127; 0,460)	1,14	0,258	2,44
log(n_work)	0,174	0,209	(-0,246; 0,595)	0,83	0,408	2,46
Cons_Term	-0,112	0,123	(-0,359; 0,136)	-0,91	0,368	1,01

S	R-sq.	R-sq. (adjusted)	PRESS	R-sq. (pred)	AICc	BIC
0,431612	40,84%	35,59%	10,0638	28,98%	66,56	76,08

Table D.8: *Equation of regression – Log(Cons_H2O).*

It can be seen that the AIC and BIC indicator is raised for Cons_H2O models even if R^2 increases.

Appendix E

E HDKR Model

E.1 First parameters

Sky models are mathematical models that represent the atmospheric behaviour, which might directly affect the irradiation received by solar collectors, thus understanding them, is essential for Engineers in this and related fields. The Hay and Davies, Klucher and Reindl (HDKR) Isotropic sky model was a step forward in a more precise mathematical approximation of the phenomena that built on Liu & Jordan's equation (other Sky model). It is an anisotropic model that takes into account circumsolar and horizon brightening components into the total irradiance at the tilted array.

To evaluate the real solar potential of the area it is necessary to obtain the effective irradiation, applying the HDKR model to the global horizontal irradiation provided by the Servei Meterològic de Catalunya. This irradiation is defined as $G[pyro\ 802]$ and it is captured by the pyrometer of the nearest weather station in the area.

This is a Solar Radiance Model that uses the empirical data results, which are shown in the Appenix B. In a preliminary part of the project, it is necessary to design a series of calculations with the general data of the zone that are shown in Table E.1, for obtaining the expected irradiance.

β (tilt) of PV panel	41°
Azimuth	0°
Latitude (Φ)	41,60°
Longitude	2,27°
Day of the Year	N
Solar Irradiation (Gsc)	1367 W/m^2
Solar azimuth (ϒ)	0°

Table E.1: *Solar features of the location.*

The first calculation to be made is the solar time or solar time, since the data provided in Table E.1 were based on the Granollers time zone. All days of the year N were calculated separately and knowing N, it is possible to calculate the parameter B with equation E.1. Consequently, the difference between the solar time and the Granollers standard time depends on the parameter E in the equation E.2, which takes into account the rotation of the Earth, the difference in longitude with the local meridian and the adjustment of the standard time due to the DLS (daylight saving time). Last one parameter is zero, since the days are in wintertime.

Other necessary parameters will be the declination angle δ, which is calculated using the equation E.3 and the average solar radiation G_{on} on the horizontal surface, which is determined in the equation E.4, as a function of B and the solar constant G_{sc}, located in Table E.1.

$$B = (N-1) \cdot \frac{360}{365} \qquad \text{(E.1)}$$

Where N is the number of the day$(1 \leq N \leq 365)$ and $\frac{360}{365}$ the ratio to approximate standard days to solar days.

$$E = 2.292(0.0075 + 0.1868cosB - 3.2077sinB - 1.4615cos2B - 4.089sin2B) \qquad \text{(E.2)}$$

$$\delta = \frac{180}{\pi}(0.006918 - 0.399912cosB + 0.070257sinB - 0.006758cos2B + 0.000907sin2B - 0.002697cos3B + 0.00148sin3B) \qquad \text{(E.3)}$$

$$G_{on} = G_{sc}(1.000110 + 0.034221cosB + 0.001280sinB + 0.000719cos2B + 0.00007sin2B \qquad \text{(E.4)}$$

The solar time is slightly different from the time the clock gives us, being the one to consider in these studies with the equation E.5.

$$t_{solar} = t_{clock} + E + 4(L_{st} - L_{loc}) - 60 \cdot DLS \qquad \text{(E.5)}$$

Where t_{clock} is standard time, $(L_{st} - L_{loc})$ the difference between longitude of the zone with local meridian and DLS the daylight saving time.

Also, related, from the solar time we can compute the hour angle ω, the angle of the sun in relation to its position at noon, which is from where the time is measured. This angle is defined too, as the angle between the meridian parallel to sun rays and the meridian containing the observer.

$$\omega = 15 \cdot t_{solar} - 180 \qquad \text{(E.6)}$$

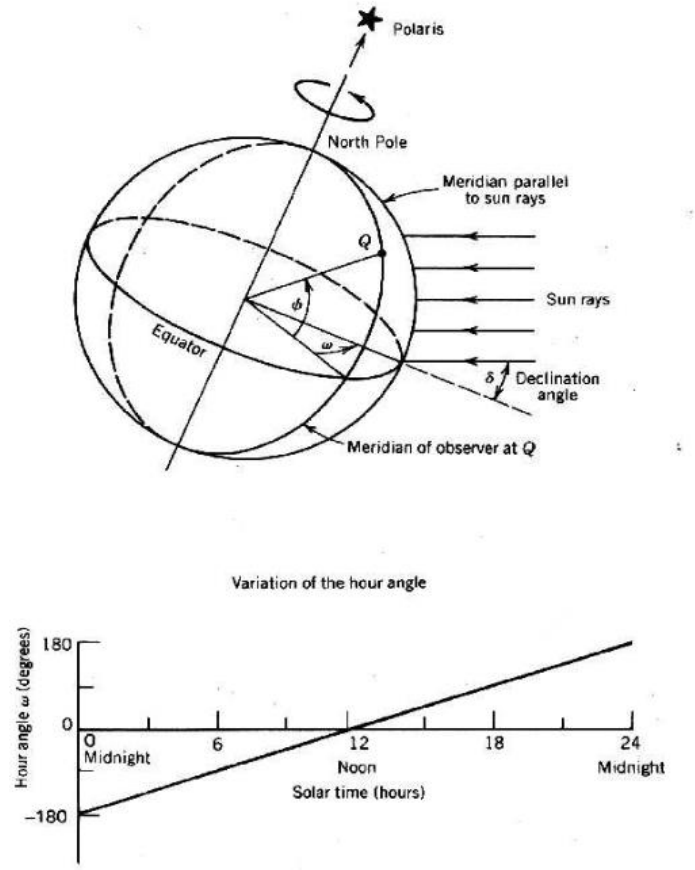


Figure E.1: *The Hour Angle (ω) and its variation.*

The zenith angle (θ_z) is calculated using the expression of equation E.7 and all angles are related to Fig. E.2.

$$cos\theta_z = \cos\delta\cos\omega\cos\phi + \sin\delta\sin\phi \tag{E.7}$$

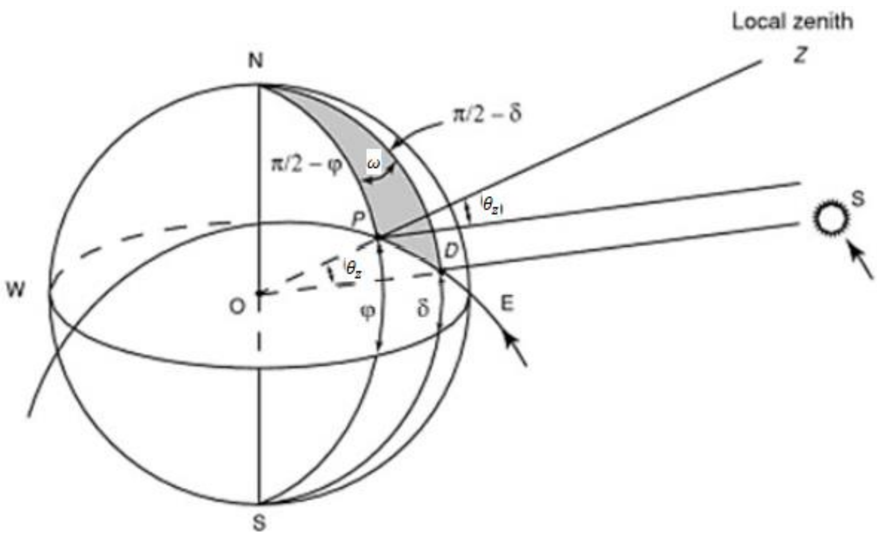


Figure E.2: *Zenith angle related to declination and hour angle.*

The angle between the sun beams and the surface of the panel are given by θ using the calculated results in the equation E.8:

$$cos\theta \;= sin\,\delta\, sin\,\phi\, cos\,\beta - sin\,\delta\, cos\,\phi\, sin\,\beta\, cos\,\gamma + cos\,\delta\, cos\,\phi\, cos\,\beta\, cos\,\omega + cos\,\delta\, sin\,\phi\, sin\,\beta\, cos\,\gamma\, cos\,\omega + cos\,\delta\, sin\,\beta\, sin\,\gamma\, sin\,\omega \tag{E.8}$$

With the calculated angles values, we can compute the values for R_b , the relation between the cosines of the beam's inclination and the zenith angle, and the extra-terrestrial normal irradiance, G_o.

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{E.9}$$

$$G_o = G_{sc}\left[1 + 0.033\cos\left(\frac{360\cdot n}{365}\right)\right](\cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta) \tag{E.10}$$

E.2 Final equations and calculations

From this point, we start implementing the HDKR model. The clearness index, indication of the state of the sky, can derived from the relation between the calculated and the measured irradiance on the horizontal surface:

$$k_t = \frac{G[pyro802]}{G_o} \tag{E.11}$$

In order to calculate the irradiance on an inclined surface, the ratio mentioned above is necessary and it is given as a function of k_t. The constraints of equation E.12 are obtained from source [15] **(Sokol, 2012)** that it is based on Erbs model (1982), Reindl model (1990) and Orgill and Holands model (1977).

$$\frac{G_d}{G} = \begin{cases} 1.0 - 0.09k_T & k_T \le 0.22 \\ 0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4 & 0.22 < k_T \le 0.80 \\ 0.165 & k_T > 0.8 \end{cases} \tag{E.12}$$

The different components of irradiation can be obtained from equations E.13 and E.14.

$$G_d = \frac{G_d}{G}\cdot G[pyro\ 802] \tag{E.13}$$

$$G_b = G - G_d \tag{E.14}$$

The total irradiance can be calculated using the HDKR model in the equation E.15:

$$\frac{G_T}{G} = \left[1 - \frac{G_d}{G}(1 - A_i)\right]R_b + \frac{G_d}{G}(1 - A_i)\left(\frac{1+\cos\beta}{2}\right)\left[1 + \sqrt{\frac{G_b}{G}}sin^3\left(\frac{\beta}{2}\right)\right] + \rho_g\left(\frac{1-\cos\beta}{2}\right) \tag{E.15}$$

Where $A_i = \frac{G_b}{G_o}$, and $\rho_g = 0.4$, the ground view factor.

This model calculates the total irradiance considering the influence of each component, direct, diffuse and ground reflect. The influence of those components can be calculated with equations E.16 and E.17:

$$\%G_b = \frac{(G_b + A_i \cdot G_d)R_b}{G_t}$$

$$\%G_b = \frac{\left(G_d(1-A_i)\cdot\frac{(1+\cos\beta)}{2}\cdot\left[(1+\sqrt{\frac{G_b}{G[pyro802]}}\cdot\left(\sin\frac{\beta}{2}\right)^3\right]\right)}{G_t} \tag{E.16}$$

$$\%G_g = \frac{G[pyro802]\cdot\rho_g\cdot\left(\frac{1-\cos\beta}{2}\right)}{G_t} \tag{E.17}$$

The values for the tilted surface are calculated by multiplying the percentages of each component by the total irradiance (G_T). From that, we can compute the effective values of irradiance, which takes into consideration the dirtiness of the surface and the angle of incidence of the solar rays.

The relative transmittance ($F_{\tau,b}$) used in the equation E.18, to calculate the direct effective irradiance was calculated by assuming a mean dust or dirt level a_r of value 0.21 and multiplied by a normal relative transmittance factor $\frac{T_{dirt}}{T_{clean}}$ of value 0.97.

$$F_{\tau,b} = 1 - \frac{\exp\left(-\frac{\cos\theta}{a_r}\right) - \exp\left(-\frac{1}{a_r}\right)}{1-\exp(-\frac{1}{a_r})} \tag{E.18}$$

$$F_{\tau,d} = 0.9$$

$$F_{\tau,g} = 0.92$$

$$\frac{T_{dirt}}{T_{clean}} = 0.97$$

The effective total irradiance is given by equation E.19, where G_b is the direct irradiance, G_d the diffuse irradiance and G_g the reflected irradiance referring to the ground. Finally, it is necessary to multiply the different components of G_T by their relative transmittance, to calculate the effective irradiance $G_{t\ eff}$ and take into account the different losses.

$$G_{t\ eff} = G_b * F_{\tau,b} * \frac{T_{dirt}}{T_{clean}} + G_d * F_{\tau,d} + G_g * F_{\tau,g} \tag{E.19}$$

Appendix F

F Hydraulic and Topographic Map

F.1 Hydraulic map of Granollers

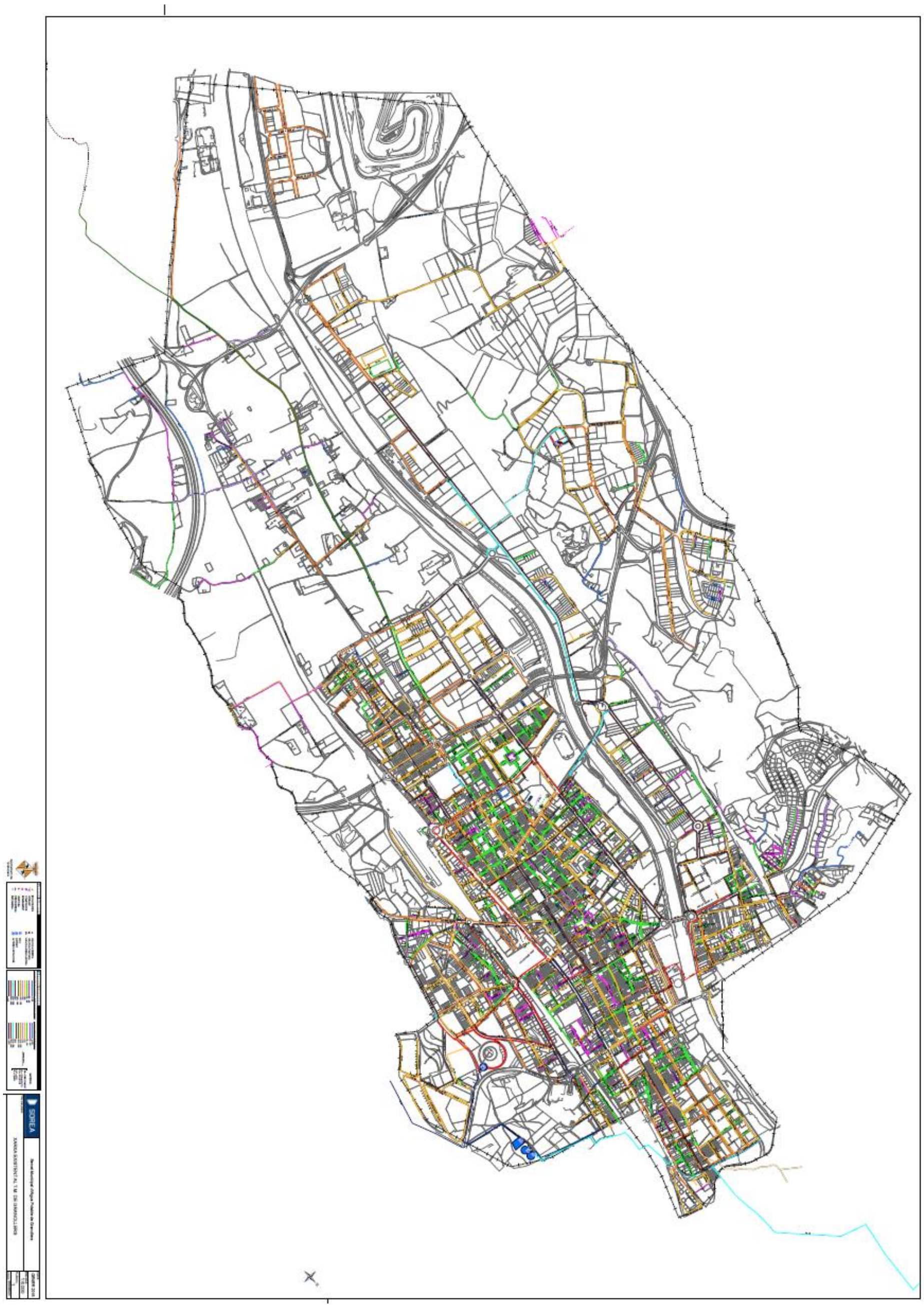


Figure F.1: *Hydraulic map of Granollers.*

F.2 Topographic map of industrial areas

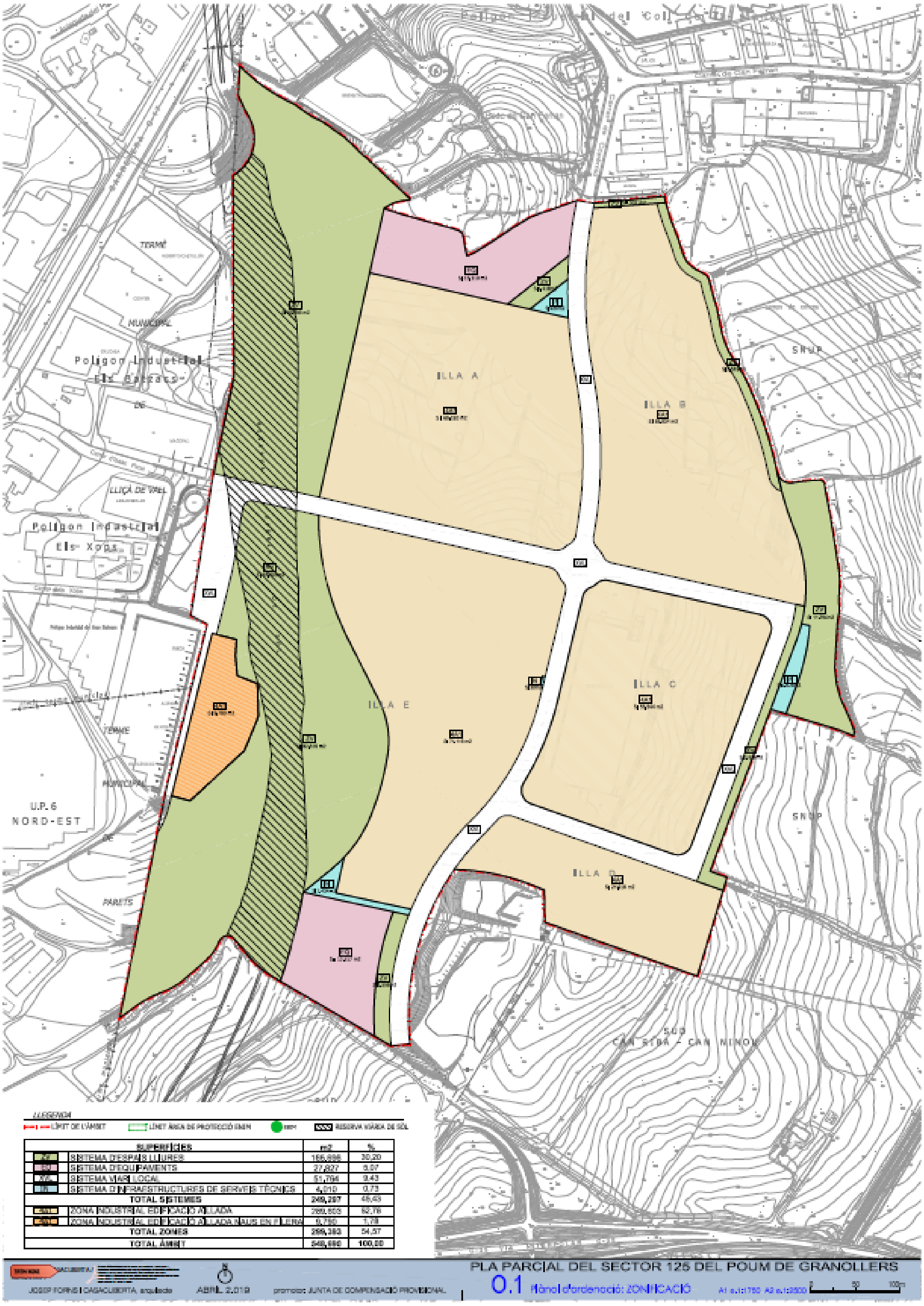


__Figure F.2:__ Topographic map of industrial areas: Coll de la Manya and Font del Ràdium.

F.3 Optimal Pipes and Nodes of Hydraulic map

Label	Start Node	Stop Node	Diameter (mm)	Material	Flow (L/s)	Velocity (m/s)	Headloss Gradient (m/m)	Length (m)
C-22	J-55	J-47	150	Ductile Iron	3,12	0,18	0	10
C-24	J-86	J-53	150	Ductile Iron	3,97	0,22	0	10
C-28	J-71	J-92	150	Ductile Iron	11,93	0,68	0,004	10
C-52	J-6	J-105	150	Asbestos Cement	3,72	0,21	0	70
C-83	PMP-1	J-71	200	Asbestos Cement	12,02	0,38	0,001	40
C-86	J-85	J-86	150	Ductile Iron	9,05	0,51	0,002	16
C-92	J-53	H-8	150	Ductile Iron	3,89	0,22	0	130
C-93	J-40	J-17	150	Ductile Iron	3,79	0,21	0	16
C-96	J-17	J-8	150	Ductile Iron	3,52	0,2	0	10
C-97	J-43	J-106	150	Ductile Iron	2,72	0,15	0	70
C-99	J-8	H-9	150	Ductile Iron	3,06	0,17	0	100
C-100	H-9	J-43	150	Ductile Iron	3,03	0,17	0	40
C-113(1)	J-65	H-15	150	Ductile Iron	3,33	0,19	0	84
C-113(2)	H-15	J-21	150	Ductile Iron	3,32	0,19	0	2
P-48	J-38	J-55	150	Ductile Iron	3,68	0,21	0	70
P-52	H-8	J-40	150	Ductile Iron	3,87	0,22	0	2
C-70(1)	J-85	H-25	100	Ductile Iron	2,68	0,34	0,002	100
C-70(2)	H-25	J-46	100	Ductile Iron	2,65	0,34	0,001	80
P-55	T-1	PMP-1	152,4	Asbestos Cement	10,17	0,56	0,002	1

Table F.1: *Pipes with a flow rate greater tan 2,5 L/s.*

Label	Elevation (m)	Demand (L/s)	Hydraulic Grade (m)	Pressure (m H2O)
J-6	145,5	0,04	174,26	29
J-8	136,5	0,04	174,32	38
J-16	148,5	0,04	174,19	26
J-17	139	0,02	174,32	35
J-21	147,7	0,68	174,2	26
J-23	126,5	0,04	174,31	48
J-40	138	0,04	174,33	36
J-43	141,3	0,03	174,28	33
J-65	148,1	0,04	174,22	26
J-78	125,8	0,04	174,31	48
J-79	126,5	0,04	174,31	48
J-97	147,3	0,24	174,22	27
J-104	135,8	0,04	174,33	38
J-105	148,1	0,04	174,23	26
J-106	143	0,04	174,27	31
J-109	147,3	0,04	174,19	27
J-125	135,9	0,29	174,27	38

J-126	125,2	0,02	174,31	49
J-131	143	0,25	174,32	31
J-135	147,7	0,45	173,8	26
J-141	147,5	0,04	174,22	27
J-142	144	0,04	174,26	30
J-143	144	0,43	174,26	30
J-152	120,8	0,04	217,72	97
J-156	164,1	0,14	217,72	54

Table F.2: *Nodes with the established constraint of minimum of 25 mWc.*

	ID	Label	Length (Scaled) (m)	Start Node	Stop Node	Diameter (mm)	Material	Darcy-Weisbach e (m)	Has Check Valve?	Minor Loss Coefficient (Local)	Flow (L/s)	Velocity (m/s)	Headloss Gradient (m/m)	Has User Defined Length?	Length (User Defined) (m)
131: C-8	131	C-8	1	J-61	J-62	150,0	Ductile Iron	0,0001	☐	0,150	0,15	0,01	0,000	☑	10
134: C-9	134	C-9	1	J-63	J-64	150,0	Ductile Iron	0,0001	☐	0,150	0,00	0,00	0,000	☑	8
139: C-10	139	C-10	1	J-66	J-67	40,0	Synthetic ma	0,0001	☐	0,150	0,00	0,00	0,000	☑	10
152: C-14	152	C-14	2	J-74	J-75	150,0	Ductile Iron	0,0001	☐	0,150	0,21	0,01	0,000	☑	8
155: C-15	155	C-15	2	J-76	J-77	32,0	Synthetic ma	0,0001	☐	0,150	0,00	0,00	0,000	☑	10
158: C-16	158	C-16	2	J-46	J-19	100,0	Ductile Iron	0,0001	☐	0,150	3,80	0,48	0,003	☑	10
159: C-17	159	C-17	2	J-78	J-79	100,0	Asbestos Ce	0,0001	☐	0,150	0,00	0,00	0,000	☑	10
166: C-18	166	C-18	2	J-81	J-57	100,0	Ductile Iron	0,0001	☐	0,150	3,07	0,39	0,002	☑	10
177: C-20	177	C-20	2	J-87	J-88	100,0	Asbestos Ce	0,0001	☐	0,150	-0,71	0,09	0,000	☑	8
180: C-21	180	C-21	2	J-28	J-10	150,0	Ductile Iron	0,0001	☐	0,150	0,01	0,00	0,000	☑	10
181: C-22	181	C-22	3	J-55	J-47	150,0	Ductile Iron	0,0001	☐	0,150	9,63	0,55	0,002	☑	10
184: C-23	184	C-23	2	H-19	J-30	100,0	Asbestos Ce	0,0001	☐	0,150	-0,69	0,09	0,000	☑	10
185: C-24	185	C-24	2	J-86	J-53	150,0	Ductile Iron	0,0001	☐	0,150	5,53	0,31	0,001	☑	10
186: C-25	186	C-25	2	J-13	J-55	150,0	Ductile Iron	0,0001	☐	0,150	3,28	0,19	0,000	☑	10
187: C-26	187	C-26	2	H-18	J-90	100,0	Asbestos Ce	0,0001	☐	0,150	0,08	0,01	0,000	☑	10
189: C-27	189	C-27	2	J-91	J-76	32,0	Synthetic ma	0,0001	☐	0,150	0,00	0,00	0,000	☑	10

Figure F.3: *Defined table in Watergems of the hydraulic map pipes.*

Appendix G

G Clustering of Observations

Paso	Número de conglomerados	Nivel de semejanzal	Nivel de distancia	Conglomerados incorporados		Nuevo conglomerado	Número de obs. en el conglomerado nuevo
1	49	99,7168	3,69	14	31	14	2
2	48	99,6550	4,50	7	24	7	2
3	47	99,4888	6,67	22	50	22	2
4	46	99,3913	7,94	12	16	12	2
5	45	99,3638	8,30	14	20	14	3
6	44	99,3596	8,35	32	41	32	2
7	43	99,3465	8,52	10	34	10	2
8	42	99,2997	9,13	13	18	13	2
9	41	99,2473	9,82	4	9	4	2
10	40	99,2335	10,00	27	47	27	2
11	39	99,2057	10,36	25	44	25	2
12	38	99,1950	10,50	45	48	45	2
13	37	99,1583	10,98	23	39	23	2
14	36	99,1140	11,56	37	38	37	2
15	35	99,0024	13,01	35	36	35	2
16	34	98,9661	13,49	19	37	19	3
17	33	98,9010	14,34	2	26	2	2
18	32	98,6830	17,18	3	22	3	3
19	31	98,5778	18,55	5	7	5	3
20	30	98,5744	18,60	14	33	14	4
21	29	98,4500	20,22	32	40	32	3
22	28	98,4427	20,31	13	46	13	3
23	27	98,4272	20,52	2	25	2	4
24	26	98,3229	21,88	17	23	17	3
25	25	98,2338	23,04	6	11	6	2
26	24	98,1862	23,66	17	27	17	5
27	23	98,0930	24,88	8	42	8	2
28	22	97,7527	29,31	28	45	28	3
29	21	97,7240	29,69	12	21	12	3
30	20	97,6644	30,47	2	5	2	7
31	19	97,6060	31,23	1	35	1	3
32	18	97,3598	34,44	3	10	3	5
33	17	97,3590	34,45	4	30	4	3
34	16	96,9676	39,56	4	14	4	7
35	15	96,5145	45,47	13	28	13	6
36	14	95,6030	57,35	19	32	19	6
37	13	95,5660	57,84	2	6	2	9
38	12	94,4511	72,38	4	17	4	12
39	11	94,2503	75,00	12	13	12	9
40	10	93,7387	81,67	8	29	8	3
41	9	92,2112	101,60	2	3	2	14
42	8	91,9926	104,45	1	12	1	12
43	7	91,6857	108,45	15	43	15	2
44	6	85,5000	189,14	2	4	2	26
45	5	85,2943	191,82	8	19	8	9
46	4	74,5995	331,33	1	2	1	38
47	3	65,6784	447,70	15	49	15	3
48	2	56,9862	561,08	1	8	1	47
49	1	0,0000	1304,42	1	15	1	50

Table G.1: *Amalgation steps of Clustering.*

	Número de observaciones	Dentro de la suma de cuadrados del conglomerado	Distancia promedio desde el centroide	Distancia máxima desde centroide
Conglomerado1	12	13583,2	30,5973	54,4686
Conglomerado2	14	15875,3	30,9131	56,2319
Conglomerado3	12	6713,7	21,3786	39,3150
Conglomerado4	3	3996,8	34,5702	49,5811
Conglomerado5	2	5881,1	54,2267	54,2267
Conglomerado6	6	3219,5	22,2919	29,2186
Conglomerado7	1	0,0	0,0000	0,0000

Table G.2: *Final partition of Clustering.*

Variable	Conglomerado1	Conglomerado2	Conglomerado3	Conglomerado4	Conglomerado5
Pk_n	283,915	58,7434	162,050	515,046	908,774
pk_T	8,967	8,8571	22,817	33,633	0,300

Variable	Conglomerado6	Conglomerado7	Centroide principal
Pk_n	401,421	1306,92	265,042
pk_T	18,100	3,40	14,378

Table G.3: *Group centroids of Clustering.*

	Conglomerado1	Conglomerado2	Conglomerado3	Conglomerado4	Conglomerado5
Conglomerado1	0,00	225,17	122,65	232,443	624,919
Conglomerado2	225,17	0,00	104,25	456,975	850,074
Conglomerado3	122,65	104,25	0,00	353,162	747,064
Conglomerado4	232,44	456,97	353,16	0,000	395,137
Conglomerado5	624,92	850,07	747,06	395,137	0,000
Conglomerado6	117,86	342,80	239,42	114,682	507,665
Conglomerado7	1023,02	1248,19	1145,04	792,453	398,160

	Conglomerado6	Conglomerado7
Conglomerado1	117,860	1023,02
Conglomerado2	342,802	1248,19
Conglomerado3	239,418	1145,04
Conglomerado4	114,682	792,45
Conglomerado5	507,665	398,16
Conglomerado6	0,000	905,62
Conglomerado7	905,620	0,00

Table G.4: *Distances between conglomerate centroids.*

Appendix H

H Data Sheets

H.1 Turbine HE Inline HP

HE | Technical specifications

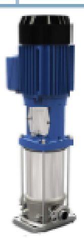
BATTERY CHARGING TURBINE

TECNOTURBINES POWERING WATER

Turbine specifications

TURBINE TYPE	INLINE	INLINE HP
TECHNICAL FEATURES		
DESIGN	In line installation with the existing pipe	
CONSTRUCTION TYPE	Vertical or horizontal axis	
COUPLING SYSTEM	Flanges accordins to EN1092-2	Flanges accordins to EN1092-2 or thread according to EN ISO 228-1
INLET AND OUTLET DIAMETERS mm (according to models)	32 to 100	25 to 100
WATERTIGHTNESS	Mechanic seal	
BEARINGS	Standard Ball Bearing	
OPERATING FLUIDS	Potable water, irrigation water, river water, hot sanitary water sanitaria and cooling water	
MATERIALS		
CASING COVER	Cast iron	Inox steel AISI 304
IMPELLER	Cast iron , bronze or stainless steel	Inox steel AISI 304
SHAFT	Tempered steel	Inox steel AISI 304
GENERATOR COUPLING	Cast iron	
SEALING ELEMENTS	DPAF, asbestos free	EPDM
OPERATING CONDITIONS (depending on model)		
PRESSURE DROP RANGE [m]	5 to 40	5 to 300
FLOW RANGE [litres/sec]	4 to 20	1 to 8
MAXIMUM PRESSURE (bar)	16	16 to 40
SPEED RANGE [RPM]	1500 or 3000	1500 or 3000
FLUID TEMPERATURE (°C)	-30 to 140	-20 to 140
GLOBAL EFFICENCY (%)	40 to 65	25 to 55

TURBINE INLINE



TURBINE INLINE HP

Figure H.1: *Data sheet of Turbine HE Inline HP.*

H.2 Turbine Micro Regen Inline HP

Hydro Regen | Technical specifications

TURBINE FOR FEEDING INTO THE GRID OR SELF-CONSUMPTION

TECNOTURBINES POWERING WATER

Turbine specifications

TURBINE TYPE	INLINE	INLINE R	INLINE HP
ASSOCIATED CONTROL SYSTEM	Microregen or Hydroregen	Hydroregen	Microregen or Hydroregen
TECHNICAL FEATURES			
DESIGN	In line installation with the existing pipe		
CONSTRUCTION TYPE	Vertical or horizontal axis	Vertical axis	Vertical or horizontal axis
COUPLING SYSTEM	Flanges depending on EN1092-2		Flanges according to EN1092-2 or thread according to EN ISO 228-1
INLET AND OUTLET DIAMETERS (mm) (according to models)	32 to 200	150 to 350	25 to 125
WATERTIGHTNESS	Mechanical seal		
BEARINGS	Standard Ball Bearing		
OPERATING FLUIDS	Potable water, irrigation water, river water, hot sanitary water sanitaria and cooling water		
MATERIALS			
CASING COVER	Cast iron		Stainless steel AISI 304
IMPELLER	Cast iron, bronze or stainless steel		Stainless steel AISI 304
AXIS	Tempered steel		Stainless AISI 304
OPERATING FLUIDS	Cast iron		Cast iron
BEARINGS	DPAF, asbestos free		EPDM
OPERATING CONDITIONS (depending on model)			
PRESSURE DROP RANGE [m]	10 to 198	10 to 135	25 to 400
FLOW RANGE [litres/sec]	8 a 150	105 to 500	1 to 45
MAXIMUM PRESSURE [bar]	16	16 to 25	16 to 40
SPEED RANGE [RPM]	1500 or 3000	1000 to 1500	1500 or 3000
FLUID TEMPERATURE [ºC]	-30 to 140		-20 to 140
GLOBAL EFFICENCY [%]	50 to 75	70 to 78	45 to 68

INLINE TURBINE INLINE R TURBINE INLINE HP TURBINE

Figure H.2: *Data sheet of Turbine Micro Regen Inline HP.*

H.3 Photovoltaic Panels: SHARP ND250-A5

SHARP

ND-Serie A5 (60 Zellen)

250 | 245 | 240 | 235 | 230 | 225 | 220 W

Polykristalline Silizium-Photovoltaikmodule

Solarstrom – ja bitte!

Weil er das Klima schützt.

Innovationen vom Photovoltaikpionier

Als Solarspezialist mit mehr als 50 Jahren Erfahrung in der Photovoltaik (PV) trägt Sharp entscheidend zu wegweisenden Fortschritten in der Solartechnologie bei.

Sharp Photovoltaikmodule der ND-Serie sind für Einsatzbereiche mit hohem Leistungsbedarf ausgelegt. Diese polykristallinen Qualitäts-Module produzieren selbst unter anspruchsvollen Einsatzbedingungen einen dauerhaften, zuverlässigen Ertrag.

Sämtliche Modultypen der Sharp ND-Serie bieten technisch wie wirtschaftlich eine optimale Systemintegration und eignen sich für die Montage in netzgekoppelten PV-Anlagen.

EUPD RESEARCH
TOP BRAND PV
MODULE
2011

Produktmerkmale

- Hochleistungs-Photovoltaikmodule aus polykristallinen (156,5 mm)² Silizium-Solarzellen mit Modulwirkungsgraden bis zu 15,2 %.
- 3 Busbar Technologie zur Erhöhung der Leistungsausbeute.
- Antireflexbeschichtung zur Erhöhung der Lichtabsorption.
- Garantierte positive Leistungstoleranz von 0 bis +5 %. Es werden nur Module geliefert, die in der Produktion mindestens die spezifizierte Leistung oder mehr erreicht haben.
- Die Leistungssortierung erfolgt in 5-Watt-Schritten.
- Verbesserte Temperaturkoeffizienten für weniger Leistungsverluste bei höheren Temperaturen.
- Hohe Effizienz auch bei geringerer Einstrahlung.

Qualität von Sharp

Ständige Kontrollen garantieren eine gleichbleibend hohe Qualität. Jedes Modul wird optisch, mechanisch und elektrisch geprüft. Sie erkennen es am Original Sharp Label, der Seriennummer und der Sharp Garantie:

- 10 Jahre Produktgarantie
- 25 Jahre lineare Leistungsgarantie
  - Mindestens 96 % der spezifizierten Minimalleistung im ersten Jahr
  - Höchstens 0,667 % jährliche Leistungsabnahme in den folgenden 24 Jahren
  - Mindestens 80 % der spezifizierten Minimalleistung nach 25 Jahren

Zertifikate und Zulassungen

Alle Module sind getestet und zertifiziert nach

- IEC/EN 61215 und IEC/EN 61730, Anwendungsklasse A
- Schutzklasse II
- CE

Sharp ist zertifiziert nach

- ISO 9001:2008 und ISO 14001:2004

Stand: Januar 2012

Deutschland: **INFO-HOTLINE** Mo.–Fr. von 8–20 Uhr **01805 / 01 52 22** | **INFO-FAX 01805 / 38 32 38** (0,14 €/Min. aus dem deutschen Festnetz, max. 0,42 €/Min. aus dem deutschen Mobilfunknetz)

Österreich: **INFO-HOTLINE** Mo.–Fr. von 8–20 Uhr **0820 / 40 06 40** (0,145 €/Min.) | **INFO-FAX 0820 / 24 62 59** (0,145 €/Min. aus dem Festnetz Österreichs, Anrufe aus dem Mobilfunknetz ggf. teurer)

***Figure H.3**: Data sheet of PV panel SHARP ND250-A5 (1).*

Elektrische Daten (STC)

		ND-R250A5	ND-R245A5	ND-R240A5	ND-R235A5	ND-R230A5	ND-R225A5	ND-R220A5	
Nennleistung	P_{max}	250	245	240	235	230	225	220	W_p
Leerlaufspannung	V_{OC}	37,6	37,3	37,2	36,8	36,4	36,0	35,6	V
Kurzschlussstrom	I_{SC}	8,68	8,62	8,57	8,49	8,41	8,33	8,25	A
Spannung bei maximaler Leistung	V_{mpp}	30,9	30,7	30,4	30,3	30,3	30,2	30,0	V
Strom bei maximaler Leistung	I_{mpp}	8,10	7,99	7,90	7,76	7,61	7,46	7,35	A
Wirkungsgrad Modul	η_m	15,2	14,9	14,6	14,3	14,0	13,7	13,4	%

STC = Standard-Testbedingungen: Einstrahlung 1.000 W/m², AM 1,5, Zelltemperatur 25 °C.
Die elektrischen Eigenschaften liegen innerhalb von ±10% der angegebenen Werte für I_{SC}, V_{OC} und 0 bis +5% für P_{max} (Messgenauigkeit der Leistung ±3%).

Elektrische Daten (NOCT)

		ND-R250A5	ND-R245A5	ND-R240A5	ND-R235A5	ND-R230A5	ND-R225A5	ND-R220A5	
Nennleistung	P_{max}	180,2	176,6	173,0	169,3	165,7	162,1	158,5	W_p
Leerlaufspannung	V_{OC}	36,7	36,4	36,4	36,0	35,6	35,2	34,8	V
Kurzschlussstrom	I_{SC}	7,0	6,96	6,92	6,85	6,79	6,72	6,66	A
Spannung bei maximaler Leistung	V_{mpp}	27,7	27,5	27,2	27,1	27,1	27,0	26,8	V
Betriebstemperatur Zelle	NOCT	47,5	47,5	47,5	47,5	47,5	47,5	47,5	°C

NOCT: Modulbetriebstemperatur bei 800 W/m² Einstrahlung, Lufttemperatur 20 °C, Windgeschwindigkeit 1 m/s.

Grenzwerte

Maximal zulässige Systemspannung	1.000 V DC
Rückstrombelastbarkeit	15 A
Betriebstemperatur	−40 bis +90 °C
Maximale mechanische Belastung	2.400 N/m²

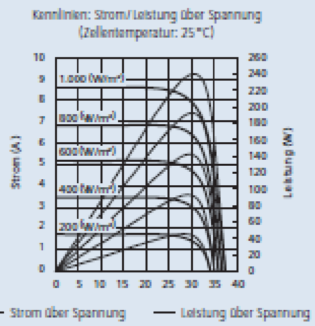
Mechanische Daten

Länge	1.652 mm (+/−3,0 mm)
Breite	994 mm (+/−2,0 mm)
Tiefe	46 mm (+/−0,8 mm)
Gewicht	19 kg

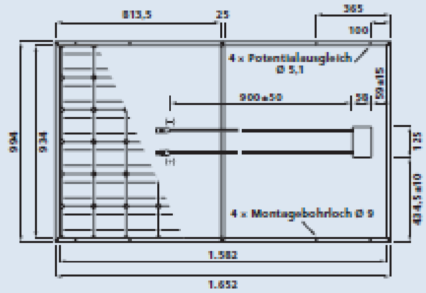
Temperatur-Koeffizient

P_{max}	−0,440 % / °C
V_{OC}	−0,329 % / °C
I_{SC}	+0,038 % / °C

Kennlinien ND-R240A5



Rückansicht



Allgemeine Daten

Zellentyp	Polykristallin, 156,5 mm × 156,5 mm, 60 Zellen in Reihe
Frontglas	Eisenarmes, vergütetes Weißglas, 3 mm
Modulrahmen	Aluminium eloxiert, silberfarben
Anschlussdose	PPE/PPO Kunststoff, IP65, 58 × 125 × 15 mm, 3 Bypass-Dioden
Anschlusskabel	4 mm², Länge 900 mm
Stecker	SMK (MC4 kompatibel), Typ CCT9901-2361F/2451F (Katalognr. P51-7H/R51-7), IP67

Bitte verwenden Sie nur SMK Stecker der genannten Serie oder MultiContactAG Steckverbinder (PV-KST04/PV-KBT04)

Registrierung

Sharp Solar garantiert über viele Jahre Sicherheit, Produktqualität und Wertstabilität – das Einzige, worum wir Sie bitten: Registrieren Sie Ihre Module mit der Seriennummer, damit wir Ihnen das Garantiezertifikat zusenden können. Registrieren Sie Ihre Module schnell und einfach unter **www.brandaddedvalue.net**.

Das Referenzbild auf der Vorderseite zeigt eine 13 kWp-Anlage in Norddeutschland.
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SolarND_60A5_D012

SHARP

Figure H.4: *Data sheet of PV panel SHARP ND250-A5 (2).*

H.4 Battery HOPPECKE 20 OPzS 2500 LA

HOPPECKE
POWER FROM INNOVATION

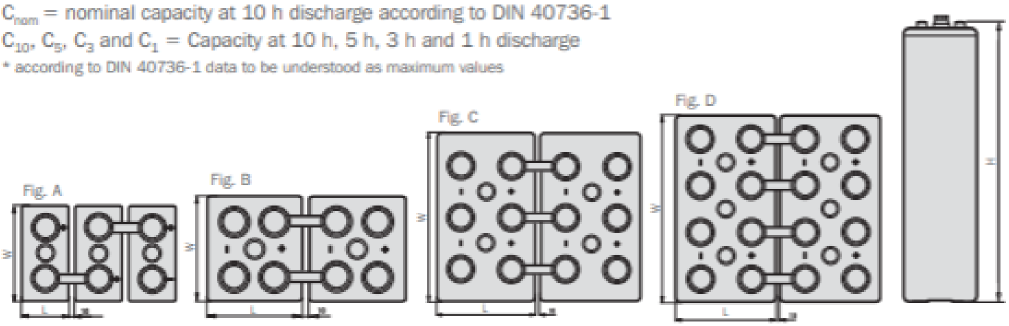
OPzS

Type Overview

Capacities, dimensions and weights

Type	C_{nom}/1.80 V Ah	C_{10}/1.80 V Ah	C_5/1.77 V Ah	C_3/1.75 V Ah	C_1/1.67 V Ah	max.* Weight kg	Weight electrolyte kg (1.24 kg/l)	max.* Length L mm	max.* Wicht W mm	max.* Height H mm	Fig.
4 OPzS 200	200	213	182	161	118	17.3	4.5	105	208	420	A
5 OPzS 250	250	266	227	201	147	21.0	5.6	126	208	420	A
6 OPzS 300	300	320	273	241	177	24.9	6.7	147	208	420	A
5 OPzS 350	350	390	345	303	217	29.3	8.5	126	208	535	A
6 OPzS 420	420	468	414	363	261	34.4	10.1	147	208	535	A
7 OPzS 490	490	546	483	426	304	39.5	11.7	168	208	535	A
6 OPzS 600	600	686	590	510	353	46.1	13.3	147	208	710	A
7 OPzS 700	700	801	691	596	411	59.1	16.7	215	193	710	B
8 OPzS 800	800	915	790	681	470	63.1	17.3	215	193	710	B
9 OPzS 900	900	1026	887	767	529	72.4	20.5	215	235	710	B
10 OPzS 1000	1000	1140	985	852	588	76.4	21.1	215	235	710	B
11 OPzS 1100	1100	1256	1086	938	647	86.6	25.2	215	277	710	B
12 OPzS 1200	1200	1370	1185	1023	706	90.6	25.8	215	277	710	B
12 OPzS 1500	1500	1610	1400	1197	784	110.4	32.7	215	277	855	B
14 OPzS 1750	1750	1881	1632	1397	914	142.3	46.2	215	400	815	C
15 OPzS 1875	1875	2016	1748	1496	980	146.6	46.7	215	400	815	C
16 OPzS 2000	2000	2150	1865	1596	1045	150.9	45.9	215	400	815	C
18 OPzS 2250	2250	2412	2097	1796	1176	179.1	56.4	215	490	815	D
19 OPzS 2375	2375	2546	2213	1895	1242	182.9	55.6	215	490	815	D
20 OPzS 2500	2500	2680	2330	1995	1307	187.3	55.7	215	490	815	D
22 OPzS 2750	2750	2952	2562	2195	1437	212.5	67.0	215	580	815	D
23 OPzS 2875	2875	3086	2678	2294	1503	216.8	65.9	215	580	815	D
24 OPzS 3000	3000	3220	2795	2394	1568	221.2	66.4	215	580	815	D
26 OPzS 3250	3250	3488	3028	2594	1699	229.6	65.4	215	580	815	D

C_{nom} = nominal capacity at 10 h discharge according to DIN 40736-1
C_{10}, C_5, C_3 and C_1 = Capacity at 10 h, 5 h, 3 h and 1 h discharge
* according to DIN 40736-1 data to be understood as maximum values



4 OPzS 200 - 6 OPzS 600
7 OPzS 700 - 12 OPzS 1500
14 OPzS 1750 - 16 OPzS 2000
18 OPzS 2250 - 26 OPzS 3250

Design life: up to 20 years

Optimal environmental compatibility - closed loop for recovery of materials in an accredited recycling system

[1] Similar to sealed lead-acid batteries

Figure H.5: *Data sheet of Battery HOPPECKE 20 OPzS 2500 LA.*

Appendix I

I Final Program

The final code of the optimization model in software Matlab is divided in 3 parts, the main code and three functions:

I.1 Minimizing function

```
function f_sum = objectiveFun(x)
    global T Cd Ce z
     d = x(4);
     e = x(8);
    for i=1:T
        z(i) = Cd(i)*d-Ce(i)*e;
    end
    f_sum = sum(z);
end
```

I.2 Payback function

```
function PB = funcionPayback(cins, gins)
       %global cins gins
       percent=1
       inv=cins
       PB=0
       while inv>0
           inv=inv-(gins*percent)
           percent=percent+0.01
           PB=PB+1
       end
end
```

I.3 IRR function

```
%TIR
function TIR = funcionTIR(cins, gins)
    %global cins gins
    percent=1
    k=[]
    k(1)=-cins
    for i=2:25
        k(i)=gins*percent
        percent=percent+0.01
```

```
    end
    TIR=irr(k)
end
```

I.4 Main code

```
% TURBINE DATA

%Power & generation of turbine connected to Grid
ptb1=2
Gtb1=[16294.6]
%Power & generation of turbine self-consumption
ptb2=0.3
Gtb2=[2260.08]
%Choose turbine
ptb=ptb1
Gtb=Gtb1

% PV DATA
Ppv=49.75
Gpv=[29023.38]

%D=input('Give matrix of consumption in kWh')
D=[17791;3929;3135;13488];

%Battery
e1=(sum(D)*1000)/(365*48*0.94*0.15);
e2=(sum(D)*1000*5)/(365*48*0.94*0.80);
E=max(e1,e2)*(48^2)*0.0000002778/2;
%B=input('Give battery capacity in kWh')
B=E*365;

%INITIAL CONSTANTS
%T=input('Give total number of periods')
T=1;
%K=input('Give total number of companies')
K=4;
%u=input('Give depth of discharge of battery')
u=0.8;
%n=input('Give battery efficiency')
n=0.94;
%G=input('Give list of total generation in kWh')
G=[Gtb+Gpv];
%Cd=input('Give list of electricity cost in €/kWh')
Cd=[0.14];
%Ce=input('Give list of surplus cost in €/kWh')
Ce=[0.06];
%b0=input('Give battery capacity in the first instant')
b0=0;

%MATRIX
mat1=[0 0 0 0 0 0 1 0;0 0 0 0 0 0 1 0; 0 0 0 0 0 0 1 0; 0 0 0 0 0 0
1 0; 0 0 0 0 0 0 1 0; 0 0 0 0 0 0 1 0; 1 1 1 1 1 1 1 1;0 0 0 0 0 0
1 0]
mat2=[inf() inf() inf() inf() inf() inf() 1 inf();inf() inf() inf()
inf() inf() inf() 1 inf(); inf() inf() inf() inf() inf() inf() 1
inf(); inf() inf() inf() inf() inf() inf() 1 inf(); inf() inf()
inf() inf() inf() inf() 1 inf(); inf() inf() inf() inf() inf()
```

```
inf() 1 inf(); 1 1 1 1 1 1 1 1;inf() inf() inf() inf() inf() inf()
1 inf()];
z=[];

%Objective function
objective = @objectiveFun ;
%@(x) sum((sum(Cd)/T)*x(4)-(sum(Ce)/T)*x(8))

% initial guess
x0 = [1000,1000,1000,1000,1000,1000,1000,1000];

% variable bounds
lb = u*B * mat1;
ub = B * mat2;

% show initial objective
disp(['Initial Objective: ' num2str(objective(x0))])

Aeq1 = [1 1 1 0 0 0 0 0];
Aeq2 = [0 0 1 1 n 0 0 0];
Aeq3 = [-n 0 0 0 1 1 1 0];
Aeq4 = [0 1 0 0 0 n 0 -1];
beq1 = G;
beq2 = sum(D);
beq3 = b0;
beq4 = 0;

% linear constraints
A = [];
b = [];
Aeq = [repmat(Aeq1,T,1); repmat(Aeq2,T,1); repmat(Aeq3,T,1);
repmat(Aeq4,T,1)];
beq = [beq1'; beq2'; repmat(beq3,T,1); repmat(beq4,T,1)];

% nonlinear constraints
nonlincon = @nlcon2;

% optimize with fmincon
%[X,FVAL,EXITFLAG,OUTPUT,LAMBDA,GRAD,HESSIAN]
% = fmincon(FUN,X0,A,B,Aeq,Beq,LB,UB,NONLCON,OPTIONS)
x = fmincon(objective,x0,A,b,Aeq,beq,lb,ub,nonlincon);

% show final objective
disp(['Final Objective: ' num2str(objective(x))])

% print solution
disp('Solution')
disp(['g_b = ' num2str(x(1))])
disp(['g_e = ' num2str(x(2))])
disp(['sum(g_k) = ' num2str(x(3))])
disp(['sum(d_k) = ' num2str(x(4))])
disp(['sum(b_k) = ' num2str(x(5))])
disp(['b_e = ' num2str(x(6))])
disp(['b = ' num2str(x(7))])
disp(['e = ' num2str(x(8))])

% FUNCTION RESULT
z=Cd*x(4)-Ce*x(8)
disp(['z = ' num2str(z)])
c=Ce*x(8)
```

```
 % COSTS TURBINA
ctb=ptb*826.42*ptb^-0.292

% COSTS PV
if Ppv>200
    cpv=0.8
elseif Ppv>=100
    cpv=1
elseif Ppv>=49.5
    cpv=1.1
elseif Ppv>=25
    cpv=1.62
elseif Ppv>=12.5
    cpv=1.85
else
    cpv=2
end

cpv_f=cpv*Ppv*1000

%BENEFITS CO2
gco2=(sum(D)-x(4))*0.428*0.19/1000

%INSTALLATION COST
cins=cpv_f+ctb
gins=c+((sum(D)-x(4))*Cd)+gco2

%PAYBACK
PB = funcionPayback(cins, gins) ;

%TIR
TIR=funcionTIR(cins, gins);

%Capçalera
if ptb==ptb1
    disp('CONNECTED TO GRID')
else
    disp('SELF-CONSUMPTION')
end
disp(['Power Turbine [kW] = ' num2str(ptb)])
disp(['Power PV installation [kWp] = ' num2str(Ppv)])
disp('--------- ')
% show final objective
disp(['Final Objective 1: ' num2str(objective(x))])
disp(['Final Objective 2: ' num2str(z)])
disp('--------- ')

% print solution
disp('Solution in kWh:')
disp(['g_b = ' num2str(x(1))])
disp(['g_e = ' num2str(x(2))])
disp(['sum(g_k) = ' num2str(x(3))])
disp(['sum(d_k) = ' num2str(x(4))])
disp(['sum(b_k) = ' num2str(x(5))])
disp(['b_e = ' num2str(x(6))])
disp(['b = ' num2str(x(7))])
disp(['e = ' num2str(x(8))])
disp('-------- ')

%Print Profit
```

```
disp(['Profit Generation [€] = ' num2str((sum(D)-x(4))*Cd)])

%Print Profit
disp(['Profit Surplus e [€] = ' num2str(c)])

%Print Profit
disp(['Profit CO2 [€] = ' num2str(gco2)])

%Print Profit
disp(['Total Profit 1st Year [€] = ' num2str(gins)])

%Print Total cost
disp(['Investment [€] = ' num2str(cins)])

%Print Payback
disp(['Payback [years] = ' num2str(PB)])

%Print TIR
disp(['TIR (%) = ' num2str(TIR*100)])
```

Appendix J

J Results

The following results are separated by different cases and study models according to solar capacity:

J.1 Case 1 – Sharing & Connected to grid

	MAXIMUM CAPACITY	LOWER CAP (50%)	LOWER CAP (25%)
Demand [kWh]	342107		
Renewable Energy to customers [kWh]	241299	137914	69712
Battery Energy to customers [kWh]	0	0	0
Total Renewable Energy [kWh]	241299	137914	69712
Electric company to customers [kWh]	105404	206489	273173
Surplus [kWh]	30648	0	0
Annual CO_2 Profit [€]	19.25	11.03	5.61
CO_2 Reduction [Tm CO_2]	101.32	58.05	29.53

***Table J.1**: Environmental results of Case 1.*

	MAXIMUM CAPACITY	LOWER CAP (50%)	LOWER CAP (25%)
Total Profit 1st Year [€]	34997	18998	9656
Total Investment [€]	350644	177444	110994
Payback [years]	10	9	11
IRR [%]	9,51	10,41	7,88

***Table J.2:** Economic results of Case 1.*

J.1.1 Case maximum solar capacity

```
CONNECTED TO GRID
Power Turbine [kW] = 0.178
Power PV installation [kWp] = 438
---------
Final Objective 1: 0
Final Objective 2: 12917.6423
---------
Solution in kWh:
```

```
g_b = 81486.3954
g_e = 30647.6927
sum(g_k) = 164702.022
sum(d_k) = 105403.5991
sum(b_k) = 76597.2116
b_e = 3.7096e-05
b = 9.0724e-08
e = 30647.6927
--------
Profit Generation [€] = 33138.4761
Profit Surplus e [€] = 1838.8616
Profit CO2 [€] = 19.2487
Total Profit 1st Year [€] = 34996.5864
Investment [€] = 350643.4996
Payback [years] = 10
TIR (%) = 9.5139
```

J.1.2 Case lower solar capacity for self-consumption of 50%

```
CONNECTED TO GRID
Power Turbine [kW] = 0.178
Power PV installation [kWp] = 222
---------
Final Objective 1: 0
Final Objective 2: 28908.3848
---------
Solution in kWh:
g_b = 40704.3324
g_e = 0.0049395
sum(g_k) = 99652.1926
sum(d_k) = 206488.4688
sum(b_k) = 38262.0624
b_e = 0.010134
b = 9.0001e-08
e = 0.014466
--------
Profit Generation [€] = 18986.5944
Profit Surplus e [€] = 0.00086794
Profit CO2 [€] = 11.0285
Total Profit 1st Year [€] = 18997.6237
Investment [€] = 177443.4996
Payback [years] = 9
TIR (%) = 10.4057
```

J.1.3 Case lower solar capacity for self-consumption of 25%

```
CONNECTED TO GRID
Power Turbine [kW] = 0.178
Power PV installation [kWp] = 111
---------
Final Objective 1: 0
Final Objective 2: 38244.1895
---------
Solution in kWh:
g_b = 13801.5474
g_e = 0.057034
sum(g_k) = 56739.1655
sum(d_k) = 273172.8208
sum(b_k) = 12973.4188
b_e = 0.035757
b = 9e-08
e = 0.090646
--------
Profit Generation [€] = 9650.7851
Profit Surplus e [€] = 0.0054388
Profit CO2 [€] = 5.6057
Total Profit 1st Year [€] = 9656.3963
Investment [€] = 110993.4996
Payback [years] = 11
TIR (%) = 7.877
```

J.2 Case 2 – Sharing & Self-Consumption

	OPTIM CAPACITY
Demand [kWh]	342107
Total Renewable Energy [kWh]	342107
Electric company to customers [kWh]	0
Surplus [kWh]	0
Annual CO_2 Profit [€]	27.82
CO_2 Reduction [Tm CO_2]	146.42

Table J.3: *Environmental results of Case 2.*

	OPTIM CAPACITY 1
Total Profit 1st Year [€]	47923
Total Investment [€]	3013592
Payback [years]	51
IRR [%]	-5.79

Table J.4: *Economic results of Case 2.*

J.2.1 Case optimal solar capacity for autonomous system

```
SELF-CONSUMPTION
Power Turbine [kW] = 0.178
Power PV installation [kWp] = 443.5
---------
Profit Generation [€] = 47894.98
Profit Surplus e [€] = 0
Profit CO2 [€] = 27.8201
Total Profit 1st Year [€] = 47922.8001
Investment [€] = 3013592.2997
Payback [years] = 51
TIR (%) = -5.7932
```

J.3 Case 3 – No Sharing & Connected to grid

J.3.1 Case maximum solar capacity

	MAXIMUM CAPACITY				
Company	MONDELEZ	RELEM	AIRNOU	PAVER	TOTAL
Demand [kWh]	153771	31250	37821	119265	**342107**
Total Renewable Energy [kWh]	83418	11482	24413	114281	**233594**
Electric company to customers [kWh]	71874	19972	13884	7270	**113000**
Surplus [kWh]	0	0	2294	35448	**37742**
Annual CO_2 Profit [€]	6.66	0.92	1.95	9.11	**18.64**
CO_2 Reduction [Tm CO_2]	35.05	4.83	10.26	47.95	**98.11**

Table J.5: *Environmental results of Case 3 for maximum solar capacity.*

	MAXIMUM CAPACITY				
Company	MONDELEZ	RELEM	AIRNOU	PAVER	MEAN
Total Profit 1st Year [€]	11472	1580	3491	17815	-
Total Investment [€]	179000	28675	63180	163600	-
Payback [years]	15	17	17	9	**14.5**
IRR [%]	4.66	3.24	3.27	10.63	**5.45**

Table J.6: *Economic results of Case 3 for maximum solar capacity.*

MONDELEZ

```
CONNECTED TO GRID
Power Turbine [kW] = 1e-06
Power PV installation [kWp] = 179
---------
Final Objective 1: 0
Final Objective 2: 10062.3059
---------
Solution in kWh:
g_b = 26953.8162
g_e = 0.57525
sum(g_k) = 58080.8086
sum(d_k) = 71873.9057
sum(b_k) = 25336.4742
b_e = 0.11299
b = 9e-08
e = 0.68145
--------
Profit Generation [€] = 11465.5932
Profit Surplus e [€] = 0.040887
Profit CO2 [€] = 6.6599
Total Profit 1st Year [€] = 11472.294
Investment [€] = 179000.0467
Payback [years] = 15
TIR (%) = 4.6596
```

RELEM

```
CONNECTED TO GRID
Power Turbine [kW] = 1e-06
Power PV installation [kWp] = 15.5
---------
Final Objective 1: 0
Final Objective 2: 2796.0779
---------
Solution in kWh:
g_b = 3617.1983
g_e = 0.11537
sum(g_k) = 8081.8163
sum(d_k) = 19972.0394
sum(b_k) = 3400.1535
b_e = 0.0129
b = 9e-08
```

```
e = 0.12749
--------
Profit Generation [€] = 1578.9145
Profit Surplus e [€] = 0.0076495
Profit CO2 [€] = 0.91712
Total Profit 1st Year [€] = 1579.8393
Investment [€] = 28675.0467
Payback [years] = 17
TIR (%) = 3.2418
```

AIRNOU

```
CONNECTED TO GRID
Power Turbine [kW] = 1e-06
Power PV installation [kWp] = 39
---------
Final Objective 1: 0
Final Objective 2: 1806.1405
---------
Solution in kWh:
g_b = 8447.8877
g_e = 2293.9868
sum(g_k) = 16472.3056
sum(d_k) = 13884.141
sum(b_k) = 7941.0143
b_e = 0.00010547
b = 9.113e-08
e = 2293.9869
--------
Profit Generation [€] = 3351.1603
Profit Surplus e [€] = 137.6392
Profit CO2 [€] = 1.9465
Total Profit 1st Year [€] = 3490.746
Investment [€] = 63180.0467
Payback [years] = 17
TIR (%) = 3.2675
```

PAVER S.L.

```
CONNECTED TO GRID
Power Turbine [kW] = 1e-06
Power PV installation [kWp] = 204.5
---------
Final Objective 1: 0
Final Objective 2: -1109.0467
```

```
---------
Solution in kWh:
g_b = 40548.1625
g_e = 35448.0546
sum(g_k) = 76166.3829
sum(d_k) = 7270.2615
sum(b_k) = 38115.2719
b_e = 0.00078975
b = 9.0015e-08
e = 35448.0554
--------
Profit Generation [€] = 15679.2634
Profit Surplus e [€] = 2126.8833
Profit CO2 [€] = 9.1074
Total Profit 1st Year [€] = 17815.2541
Investment [€] = 163600.0467
Payback [years] = 9
TIR (%) = 10.6275
```

J.3.2 Case optimal solar capacity for self-consumption of 50%

	OPTIM CAPACITY SELF-CONSUMPTION 50%				
Company	**MONDELEZ**	**RELEM**	**AIRNOU**	**PAVER**	**TOTAL**
Demand [kWh]	153771	31250	37821	119265	**342107**
Total Renewable Energy [kWh]	61776	12601	15234	47914	**137525**
Electric company to customers [kWh]	93033	18878	22860	72161	**206932**
Surplus [kWh]	0	0	0	0	**0**
Annual CO_2 Profit [€]	4.94	1.01	1.22	3.83	**11**
CO_2 Reduction [Tm CO_2]	26	5.32	6.42	20.16	**57.9**

Table J.7: *Environmental results of Case 3 for optimum solar capacity for self-consumption of 50%.*

	OPTIM CAPACITY SELF-CONSUMPTION 50%				
Company	**MONDELEZ**	**RELEM**	**AIRNOU**	**PAVER**	**MEAN**
Total Profit 1st Year [€]	8508	1733	2096	6598	**-**
Total Investment [€]	109725	37925	45788	85250	**-**
Payback [years]	13	20	20	13	**16.5**
IRR [%]	6.60	1.62	1.63	6.58	**4.11**

Table J.8*: Economic results of Case 3 for optimum solar capacity for self-consumption of 50%.*

MONDELEZ

```
CONNECTED TO GRID
Power Turbine [kW] = 1e-06
Power PV installation [kWp] = 99.75
```

```
---------
Final Objective 1: 0
Final Objective 2: 13024.661
---------
Solution in kWh:
g_b = 18417.1722
g_e = 0.0010607
sum(g_k) = 44464.2968
sum(d_k) = 93033.2963
sum(b_k) = 17312.135
b_e = 0.006823
b = 8.9999e-08
e = 0.0074744
--------
Profit Generation [€] = 8503.2785
Profit Surplus e [€] = 0.00044846
Profit CO2 [€] = 4.9392
Total Profit 1st Year [€] = 8508.2182
Investment [€] = 109725.0467
Payback [years] = 13
TIR (%) = 6.6028
```

RELEM

```
CONNECTED TO GRID
Power Turbine [kW] = 1e-06
Power PV installation [kWp] = 20.5
---------
Final Objective 1: 0
Final Objective 2: 2642.9499
---------
Solution in kWh:
g_b = 4058.4885
g_e = 0.010508
sum(g_k) = 8785.711
sum(d_k) = 18878.2257
sum(b_k) = 3814.9609
b_e = 0.018271
b = 9e-08
e = 0.027682
--------
Profit Generation [€] = 1732.0484
Profit Surplus e [€] = 0.0016609
Profit CO2 [€] = 1.0061
```

```
Total Profit 1st Year [€] = 1733.0561
Investment [€] = 37925.0467
Payback [years] = 20
TIR (%) = 1.6164
```

AIRNOU

```
CONNECTED TO GRID
Power Turbine [kW] = 1e-06
Power PV installation [kWp] = 24.75
---------
Final Objective 1: 0
Final Objective 2: 3200.3283
---------
Solution in kWh:
g_b = 4826.8587
g_e = 0.017518
sum(g_k) = 10696.4938
sum(d_k) = 22859.4961
sum(b_k) = 4537.2448
b_e = 0.0023575
b = 9e-08
e = 0.019734
--------
Profit Generation [€] = 2094.6105
Profit Surplus e [€] = 0.0011841
Profit CO2 [€] = 1.2167
Total Profit 1st Year [€] = 2095.8284
Investment [€] = 45787.5467
Payback [years] = 20
TIR (%) = 1.6303
```

PAVER SL

```
CONNECTED TO GRID
Power Turbine [kW] = 1e-06
Power PV installation [kWp] = 77.5
---------
Final Objective 1: 0
Final Objective 2: 10102.5401
---------
Solution in kWh:
g_b = 14368.3477
g_e = 0.0015636
sum(g_k) = 34408.1307
```

```
sum(d_k) = 72161.0047
sum(b_k) = 13506.2389
b_e = 0.0079552
b = 9e-08
e = 0.0090415
--------
Profit Generation [€] = 6594.5593
Profit Surplus e [€] = 0.00054249
Profit CO2 [€] = 3.8305
Total Profit 1st Year [€] = 6598.3904
Investment [€] = 85250.0467
Payback [years] = 13
TIR (%) = 6.5833
```

J.3.3 Case optimal solar capacity for self-consumption of 25%

	OPTIM CAPACITY SELF-CONSUMPTION 25%				
Company	**MONDELEZ**	**RELEM**	**AIRNOU**	**PAVER**	**TOTAL**
Demand [kWh]	153771	31250	37821	119265	**342107**
Total Renewable Energy [kWh]	31063	6344	15234	47914	**100555**
Electric company to customers [kWh]	123064	24996	22860	72161	**243081**
Surplus [kWh]	0	3	0	0	**3**
Annual CO_2 Profit [€]	2.49	0.51	1.22	3.83	**8.05**
CO_2 Reduction [Tm CO_2]	13.11	2.68	6.42	20.16	**42.37**

Table J.9: *Environmental results of Case 3 for optimum solar capacity for self-consumption of 25%.*

	OPTIM CAPACITY SELF-CONSUMPTION 25%				
Company	**MONDELEZ**	**RELEM**	**AIRNOU**	**PAVER**	**MEAN**
Total Profit 1st Year [€]	4301	876	2096	6598	-
Total Investment [€]	55000	20500	23125	62775	-
Payback [years]	13	22	11	10	**14**
IRR [%]	6.69	1.07	8.35	10.17	**6.57**

Table J.10*: Economic results of Case 3 for optimum solar capacity for self-consumption of 25%.*

MONDELEZ

```
CONNECTED TO GRID

CONNECTED TO GRID
Power Turbine [kW] = 1e-06
Power PV installation [kWp] = 50
---------
Final Objective 1: 0
Final Objective 2: 17228.9315
---------
```

```
Solution in kWh:
g_b = 6301.8216
g_e = 0.0022617
sum(g_k) = 25138.9161
sum(d_k) = 123063.8003
sum(b_k) = 5923.706
b_e = 0.0063499
b = 8.9999e-08
e = 0.0082306
--------
Profit Generation [€] = 4299.008
Profit Surplus e [€] = 0.00049383
Profit CO2 [€] = 2.4971
Total Profit 1st Year [€] = 4301.5056
Investment [€] = 55000.0467
Payback [years] = 13
TIR (%) = 6.6949
```

RELEM

```
CONNECTED TO GRID
Power Turbine [kW] = 1e-06
Power PV installation [kWp] = 10.25
---------
Final Objective 1: 0
Final Objective 2: 3499.2385
---------
Solution in kWh:
g_b = 1590.4942
g_e = 2.6721
sum(g_k) = 4848.9337
sum(d_k) = 24995.7058
sum(b_k) = 1495.0644
b_e = 0.00017419
b = 9e-08
e = 2.6723
--------
Profit Generation [€] = 875.6012
Profit Surplus e [€] = 0.16034
Profit CO2 [€] = 0.5086
Total Profit 1st Year [€] = 876.2701
Investment [€] = 20500.0467
Payback [years] = 22
TIR (%) = 1.0659
```

AIRNOU

```
CONNECTED TO GRID
Power Turbine [kW] = 1e-06
Power PV installation [kWp] = 12.5
---------
Final Objective 1: 0
Final Objective 2: 3200.3283
---------
Solution in kWh:
g_b = 4826.8587
g_e = 0.017518
sum(g_k) = 10696.4938
sum(d_k) = 22859.4961
sum(b_k) = 4537.2448
b_e = 0.0023575
b = 9e-08
e = 0.019734
--------
Profit Generation [€] = 2094.6105
Profit Surplus e [€] = 0.0011841
Profit CO2 [€] = 1.2167
Total Profit 1st Year [€] = 2095.8284
Investment [€] = 23125.0467
Payback [years] = 11
TIR (%) = 8.3503
```

PAVER S.L

```
CONNECTED TO GRID
Power Turbine [kW] = 1e-06
Power PV installation [kWp] = 38.75
---------
Final Objective 1: 0
Final Objective 2: 10102.5401
---------
Solution in kWh:
g_b = 14368.3477
g_e = 0.0015636
sum(g_k) = 34408.1307
sum(d_k) = 72161.0047
sum(b_k) = 13506.2389
b_e = 0.0079552
b = 9e-08
```

```
e = 0.0090415
--------
Profit Generation [€] = 6594.5593
Profit Surplus e [€] = 0.00054249
Profit CO2 [€] = 3.8305
Total Profit 1st Year [€] = 6598.3904
Investment [€] = 62775.0467
Payback [years] = 10
TIR (%) = 10.1681
```

J.4 Case 4 – No Sharing & Self-Consumption

	OPTIM CAPACITY				
Company	**MONDELEZ**	**RELEM**	**AIRNOU**	**PAVER**	**TOTAL**
Demand [kWh]	153771	31250	37821	119265	**342107**
Total Renewable Energy [kWh]	153771	31250	37821	119265	**342107**
Electric company to customers [kWh]	0	0	0	0	**0**
Surplus [kWh]	0	0	0	0	**0**
Annual CO_2 Profit [€]	12.51	2.54	3.08	9.70	**27.83**
CO_2 Reduction [Tm CO_2]	65.84	13.37	16.21	51.05	**146.47**

Table J.11: *Environmental results of Case 4.*

	OPTIM CAPACITY				
Company	**MONDELEZ**	**RELEM**	**AIRNOU**	**PAVER**	**MEAN**
Total Profit 1st Year [€]	21540	4378	5298	16707	-
Total Investment [€]	1394650	308898	373740	1081710	-
Payback [years]	52	56	56	52	**54**
IRR [%]	-5.97	-6.48	-6.48	-5.97	**-6.23**

Table J.12: *Economic results of Case 4.*

J.4.1 Case optimal solar capacity for autonomous system

MONDELEZ

```
SELF-CONSUMPTION
Power Turbine [kW] = 1e-07
Power PV installation [kWp] = 199.5
---------
Profit Generation [€] = 21527.94
Profit Surplus e [€] = 0
Profit CO2 [€] = 12.5047
Total Profit 1st Year [€] = 21540.4447
Investment [€] = 1394650.1112
```

```
Payback [years] = 52
TIR (%) = -5.9682
```

RELEM

```
SELF-CONSUMPTION
Power Turbine [kW] = 1e-07
Power PV installation [kWp] = 40.75
---------
Profit Generation [€] = 4375
Profit Surplus e [€] = 0
Profit CO2 [€] = 2.5412
Total Profit 1st Year [€] = 4377.5413
Investment [€] = 308898.5222
Payback [years] = 56
TIR (%) = -6.4779
```

AIRNOU

```
SELF-CONSUMPTION
Power Turbine [kW] = 1e-07
Power PV installation [kWp] = 49.25
---------
Profit Generation [€] = 5294.94
Profit Surplus e [€] = 0
Profit CO2 [€] = 3.0756
Total Profit 1st Year [€] = 5298.0156
Investment [€] = 373740.1243
Payback [years] = 56
TIR (%) = -6.4761
```

PAVER S.L.

```
SELF-CONSUMPTION
Power Turbine [kW] = 1e-07
Power PV installation [kWp] = 154.75
---------
Profit Generation [€] = 16697.1
Profit Surplus e [€] = 0
Profit CO2 [€] = 9.6986
Total Profit 1st Year [€] = 16706.7986
Investment [€] = 1081710.0791
Payback [years] = 52
TIR (%) = -5.9683
```