uc3m | Universidad Carlos III de Madrid

Bachelor in Energy Engineering

2018-2019

Bachelor Thesis

“Energy Analysis of UC3M Campus of Leganes and Colmenarejo: Introducing photovoltaic generation”

Mario Prinetti Polo

Tutor

David Santos Martín

Leganés

Abstract:

Spanish's energy market is experiencing big changes. Renewable energy sources and decentralization of production are on the rise. An example of this is PV systems for self-consumption with or without batteries, in houses or other buildings. One clear advantage of this is the reduction of transmission losses. In addition, this type of systems will serve to reduce CO_2 emissions and allow for a better implementation of electric cars in today's society.

The aim of this thesis is to analyse the solar potential of the UC3M Campus of Leganés and Campus of Colmenarejo. Installed capacity in both campus will be maximised in an attempt to achieve "full self-consumption", defined as the point where yearly energy generated and consumption level off. System Advisor Model will be used to simulate PV generation. This term is ambiguous, as it seems that it refers to independence from the grid and 100% renewable penetration. However, it is a reflection of the PV potential of the location at hand.

Spanish regulatory framework regarding the energy sector has been modified twice in the last year. The recent Royal Decree (RD 244/2019) will be explained, allowing for a better understanding of each scenario studied.

Moreover, a statistical analysis of the demand and generation for both campuses will be performed, using various tools. A Matlab script has been created for this task and to store all data found, which may serve for future work regarding the university.

Results showed that over 1MW of capacity was installed in Leganés, and around 10MW in Colmenarejo, which had land available for the panels.

From this project, it was concluded that full self-consumption is feasible in Colmenarejo (827.63MWh) but not in Leganés (7.85GWh), as demand is larger and space limited. For a combined case, using space from both campuses to meet their total demand, full self-consumption is achieved (8.68GWh).

In addition, if remuneration of excess energy (see section [1.1.2.2]) was aimed, only Colmenarejo would be an option, with a total of 11.3 MWh a year of injected energy. A 100kW system would produce no excess energy with Leganés' consumption. This means that for every scenario but the first one mentioned, all energy injected to the grid would mean losses, with the current regulatory framework.

Moreover, the use of batteries with total power capacity of 500kW in Leganés would be beneficial from an energy point of view, allowing for a reduction in injected energy of around 37MWh in the first year. For the combination of both cases, with a total power capacity of 3MWh, injections would be reduced to 1GWh annually.

Key words: Energy consumption, renewable penetration, grid injections and purchases.

Acknowledgments:

I would like to thank my parents and brother for all the support, both economical and emotional, they have given me through these years. Regardless of the results they always gave me all their love, and that is all I could ask for.

I would like to thank David Santos, my tutor, for trusting me in this project and guiding me through the difficulties faced. I have learnt a big deal from him and hope to learn more in the future.

Thanks to both Miguel Carpintero Rentería and David Rebollal Jordan, for helping me with data download and issues with the PV simulation tools, and to Santiago Bernal Parrondo, whom I had the pleasure of working with regarding Colmenarejo’s campus.

I would like to thank all my university colleagues and friends, without them, this bachelor would have been both longer and tougher. They have lighted a way through the tough years and helped me see the world differently. May we never forget our bond.

Content

1. Introduction---1
  1.1. Projects' objectives---1
  1.2. Photovoltaics today---2
    1.2.1. World---2
    1.2.2. Spain---3
2. State of the art---7
  2.1. Solar resource---7
    2.1.1. The Sun---7
    2.1.2. Solar geometry---8
    2.1.3. Solar concepts---9
  2.2. PV systems---10
    2.2.1. PV array---10
    2.2.2. Inverter---16
    2.2.3. Batteries---18
    2.2.4. Connexion and operation---18
    2.2.5. DC/AC ratio---19
    2.2.6. Performance ratio and capacity factor---20
3. Methodology---22
  3.1. Location for PV systems---22
  3.2. Load---24
  3.3. Generation---27
    3.3.1. SAM's Model Algorithm---27
    3.3.2. Shading in SAM---28
    3.3.3. System design---29
  3.4. Solar data---31
  3.5. Statistic tools---33
    3.5.1. Percentiles---33
    3.5.2. Boxplot and whiskers---33
  3.6. Batteries---34
4. Studied scenarios – Objectives and estimations---35
  4.1. Scenario 1: 100kW installed in Colmenarejo---35
  4.2. Scenario 2: 100kW installed in Leganés---35
  4.3. Scenario 3: Maximum capacity installed in Colmenarejo---35

    - 4.4. Scenario 4: Maximum capacity installed in Leganés ---------------------------- 35
    - 4.5. Scenario 5: Extra plot in Colmenarejo -- 35
    - 4.6. Scenario 6: Extra plot in Colmenarejo for both campuses ---------------------- 36
    - 4.7. Scenario 7: Maximum capacity installed in both campuses --------------------- 36
- 5. Results-- 37
    - 5.1. Generation -- 37
        - 5.1.1. Leganés --- 37
        - 5.1.2. Colmenarejo --- 42
    - 5.2. Scenarios -- 47
        - 5.2.1. Scenario 1 -- 47
        - 5.2.2. Scenario 2 -- 49
        - 5.2.3. Scenario 3 -- 51
        - 5.2.4. Scenario 4 -- 52
        - 5.2.5. Scenario 5 -- 54
        - 5.2.6. Scenario 6 -- 56
        - 5.2.7. Scenario 7 -- 57
    - 5.3. Statistical analysis -- 59
- 6. Conclusions --- 64
- 7. Future work--- 67
- 8. References -- 68

List of tables

TABLE 2-1. PV CELL EFFICIENCY 14
TABLE 3-1. VALUES FOR K VARYING WITH LATITUDE 31
TABLE 5-1. RESULTS FROM PV SYSTEM IN BETANCOURT BUILDING 38
TABLE 5-2. RESULTS FROM PV SYSTEM IN TORRES QUEVEDO BUILDING 39
TABLE 5-3. RESULTS FROM PV SYSTEM IN JUAN BENET BUILDING 40
TABLE 5-4. RESULTS FROM PV SYSTEM IN SPORTS CENTRE 41
TABLE 5-5. RESULTS FROM PV SYSTEM IN COLMENAREJO’S LIBRARY 42
TABLE 5-6. RESULTS FROM PV SYSTEM IN COLMENAREJO’S CAFETERIA 43
TABLE 5-7. RESULTS FROM PV SYSTEM IN COLMENAREJO’S STUDENT RESIDENCE 44
TABLE 5-8. RESULTS FROM PV SYSTEM IN COLMENAREJO CAMPUS’S PLOT 45
TABLE 5-9. RESULTS FROM PV SYSTEM IN EXTRA PLOT IN COLMENAREJO 46
TABLE 5-10. RESULTS FROM PV SYSTEM IN COLMENAREJO CAMPUS PARK 47
TABLE 5-11. SUMMARY OF SCENARIOS STUDIED 59
TABLE 5-12. ENERGY GENERATED FOR 20º AND 40º TILT 62
TABLE 5-13. EFFECT OF ROW SPACING ON ANNUAL ENERGY 63

List of figures:

Fig 1-1. Evolution of LCOE for renewable energy sources adapted from [4] -------------2
Fig 1-2. Global horizontal irradiation in Europe [5] --3
Fig 1-3. Installed Capacity in Spain. Source UNEF --4
Fig 2-1. Earth's orbit around the Sun through one year. Adapted from [6]-----------------7
Fig 2-2. Solar elevation throughout the year. Adapted from [7] ----------------------------8
Fig 2-3. Solar angles. Adapted from [8] ---9
Fig 2-4. PV cell, module, string and array [9] -- 10
Fig 2-5. PN-junction. Adapted from [10]-- 11
Fig 2-6. Single diode model for PV cells. Adapted from [11]------------------------------ 11
Fig 2-7. IV for solar cells. Adapted from [12] --- 12
Fig 2-8. Effect of different shading elements on IV curve. Adapted from [14]---------- 15
Fig 2-9. Square signal and sine wave output. Adapted from [15]------------------------- 16
Fig 2-10. Types of PV inverters. Adapted from [16] -- 17
Fig 2-11. MPPT for a module under partial shading. Adapted from [17] ---------------- 18
Fig 2-12. Array layout with blocking and bypass diodes. Adapted from [18] ----------- 19
Fig 2-13. Energy production of a PV system with different DC-AC ratios. Adapted from [19]-- 20
Fig 3-1. Rooftops in campus of Leganés, UC3M (Google Earth Pro) -------------------- 23
Fig 3-2. Rooftops and plots in campus of Colmenarejo, UC3M (Google Earth Pro) --- 23
Fig 3-3. Demand distribution in UC3M --- 24
Fig 3-4. Electric circuit for Leganés' buildings--- 25
Fig 3-5. Demand for Leganes and Colmenarejo in 2016----------------------------------- 25
Fig 3-6. Weekly load for both campuses --- 26
Fig 3-7. Energy savings from 2017 to 2018. Adapted from [21] -------------------------- 27
Fig 3-8. Shading losses in SAM --- 29
Fig 3-9. SunPower SPR-X21-335 parameters from SAM --------------------------------- 29
Fig 3-10. Month production with a tilt of 35º--- 30
Fig 3-11. Month production with a tilt of 70º--- 30
Fig 3-12. Module distribution -- 31
Fig 3-13. Monthly global horizontal irradiance for Meteonorm and PVGis ------------- 32
Fig 3-14. Global irradiance for Colmenarejo [PVGis] -------------------------------------- 33
Fig 3-15. Box plot with whiskers. Adapted from [27]-------------------------------------- 34
Fig 5-1. Direct capital costs in SAM -- 37
Fig 5-2. Panel arrangement in Betancourt building --- 38
Fig 5-3. Panel arrangement in Torres Quevedo building----------------------------------- 39
Fig 5-4. Panel arrangement in Juan Benet building --- 40
Fig 5-5. Panel arrangement in sports centre--- 41
Fig 5-6. Panel arrangement in Colmenarejo's library -------------------------------------- 42
Fig 5-7. Panel arrangement in Colmenarejo's cafeteria ----------------------------------- 43
Fig 5-8. Panel arrangement in Colmenarejo's student houses ----------------------------- 44
Fig 5-9. Panel arrangement in Colmenarejo campus's plot-------------------------------- 45
Fig 5-10. Panel distribution in extra plot in Colmenarejo---------------------------------- 46
Fig 5-11. Power flow in scenario 1 --- 48

Fig 5-12. Power flow in mid-August for scenario 1 -- 48
Fig 5-13. Power flow in mid-April for scenario 1--- 49
Fig 5-14. Power flow in scenario 2 -- 50
Fig 5-15. Five day period for the power flow in scenario 2--------------------------------- 50
Fig 5-16. Power flow in scenario 3 -- 51
Fig 5-17. Power flow in January for scenario 3 -- 52
Fig 5-18. Power flow in scenario 4 -- 52
Fig 5-19. Power flow for a one day period in august -- 53
Fig 5-20. Power flow for a one day period with batteries----------------------------------- 53
Fig 5-21. Effect of batteries on grid injections in scenario 4 ------------------------------- 54
Fig 5-22. Power flow in scenario 5 -- 55
Fig 5-23. Power flow full self-consumption Colmenarejo ---------------------------------- 55
Fig 5-24. Power flow in scenario 6 -- 56
Fig 5-25.Power flow on the 27th of July for scenario 6 ------------------------------------ 57
Fig 5-26. Power flow in scenario 7 -- 58
Fig 5-27. Effect of batteries on grid injections in scenario 7 ------------------------------- 58
Fig 5-28. Box plot full self-consumption for Colmenarejo --------------------------------- 59
Fig 5-29. Box plot full self-consumption both campuses ----------------------------------- 60
Fig 5-30. Percentiles for generation hour data --- 61
Fig 5-31. Monthly generation for different tilts -- 62

1. Introduction

Global warming has been an important issue in the past years and its concern is increasing day by day. The rise in emissions of greenhouse gases, the depletion of the ozone layer and the growing scarcity of fossil fuels have governments around the world searching for alternatives to conventional energy sources, even more nowadays, as energy consumption has doubled in the last 30 years. A good example of the implementation of renewable energy sources is Norway, where 96% of the electricity generation is accounted by renewables, mainly thanks to hydropower plants [1].

Photovoltaic (PV) energy has made strides in becoming a feasible energy source. Its quick development is due to its efficiency improving, its cost falling and the creation of targets focused on the fight against global warming. Price for PV panels has been in rapid decrease for the past years and grid parity has been reached in some countries already. Grid parity, applied for renewable energy sources, is defined as the moment where the price for electricity generated by an installation is equal to, or lower than, the price for energy bought from the grid.

The main disadvantage for PV is its production estimation and night time. Tools have been developed to simulate PV generation in different scenarios, an example would be the one used in this Bachelor's Thesis, System Advisor Model (SAM). On the other hand, night time production will still be an issue with PV as no generation happens. Batteries may solve partially this, however they still have a long way to go. For self-consumers, small consumer trading, meaning a more de-centralised energy market, could allow for PV to improve profitability.

1.1. Projects' objectives

The objective of this project is to provide an analysis of demand and PV estimation for UC3M Campus of Leganés and Colmenarejo. The effect such PV systems have on demand is studied. Results from generation will be compared with expected, explaining deviations and capital and installations costs will be calculated.

Demand data for three years must be downloaded from the internet and from a data platform provided by the Energy Department.

A review of the current Spanish regulatory framework and the major changes introduced with the last Royal Decree (RD) are explained. Each scenario under analysis will be allocated to one of the cases identified in the new RD to further understand its different definitions.

With the aim of improving renewable penetration, the effect of batteries will be studied through a basic energy comparison. A Matlab script has been developed to compare consumption with generation, the resulting interaction with the grid and the effect of extra batteries. Despite positive or negative results, an economic analysis of all different cases must be performed before making the decision of installing or not a self-consumption system.

Statistical analysis of demand and generation will be performed, to obtain a better understanding of each sample. With these results, a final recommendation will be given, providing solid information that backs up such decision.

Full self-consumption will be attempted with both campuses on their own. If it is not achieved in one of the campuses, a combination of both will be analysed.

1.2. Photovoltaics today

1.2.1. World

In 2018, around 100GW of PV capacity was installed all around the world, led by China, who topped with 44GW. The energy share of renewable sources for the entire production mix is around 25%, up to one third in Europe, and is being encouraged by a reduction in cost for solar and wind energy and environmental policies in many countries [2].

In Middle East, where countries have developed thanks to petroleum, an increase in PV capacity can be observed, as the post-petroleum era approaches. As installed power has doubled in the last two years (up to 3GW), countries like United Arab Emirates are setting objectives of 25% power output from clean energy sources by 2030, and 75% by 2050 [3]. These objectives, as optimistic as they may sound, are a pure reflection of how the world is changing, as one of the major suppliers of oil is already looking for alternatives to be able to keep up with the increasing energy demand.

As mentioned in the introduction, LCOE for solar energy has been reducing in the last years. As technology has become more price competitive, an increase in PV installations has been seen, both commercial and utility.

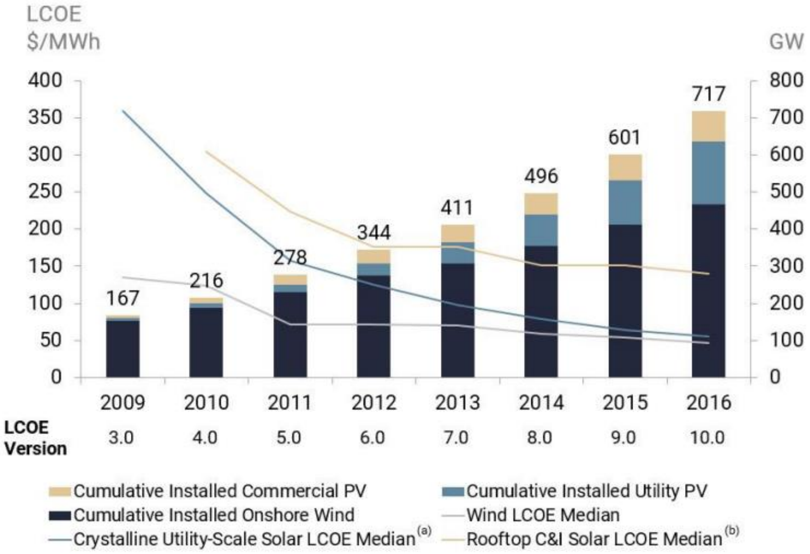


Fig 1-1. Evolution of LCOE for renewable energy sources adapted from [4]

One can see in the EU the importance of this topic, as targets have been set by the European Parliament to fight climate change, improve energy efficiency and reduce the energy bill.

The two main target packages are:

- 20-20-20 targets: 20% reduction in greenhouse gas emissions (comparing with 1990), 20% of the energy mix coming from renewables (in EU) and a 20% improvement in energy efficiency. These targets are set for 2020.
- 2030 targets: This package sets the objective at 32% of consumption of renewable energy sources and 32.5% of energy efficiency improvement.

1.2.2. Spain

In 2018, 40% of the electricity produced in Spain came from renewable energy sources. Even if only 3% was photovoltaic, Spain has progressed towards the objective of a sustainable grid set by European Union.

Due to its location and climate, Spain has an above average solar irradiance in Europe and a homogeneous distribution throughout the country. Because of this, Spain is one of the countries with most potential regarding PV.

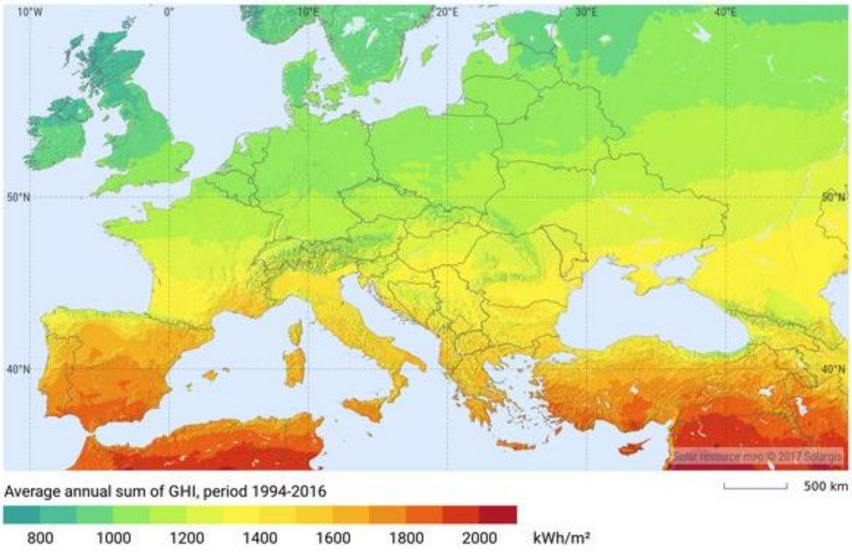


Fig 1-2. Global horizontal irradiation in Europe *[5]*

1.2.2.1. Past decade

In 2008, thanks to government subsidies and policies, Spain became the leader in PV installed capacity. An investment that seemed to enjoy high profitability but went out of control. As the government had granted many funds, it then had a considerable debt, hence changes were made and growth of solar capacity was cut to avoid a tariff deficit; price for energy lower than cost for generation. In addition, a high investment in installation was good on the short run, but bad on the medium/long run, as investigation and development would become less attractive, worsening the future of such technology.

Fig 1-3. Installed Capacity in Spain. Source UNEF

With the RD 1578/2008, legislation regarding PV installations was changed and its economic viability was deeply affected. The main changes introduced by this RD were:

- Two types of systems: ground and roof (buildings), with maximum installed power of 10MW and 2MW, respectively.
- Quota limited to 400MW in 2008, 100MW for 2009 and 60MW for 2010.

Quotas were further diminished and controlled with the RD 14/2010, access tariffs were added and financing became tougher. Bonus were eliminated with the RD 1/2012.

Finally, a tax on self-consumption was created with the RD 900/2015. This tax was named “el impuesto al sol” or “Sun tax”, as it concerned mainly solar installations, most common type of self-consumption. With the objective of reducing debt and covering for costs related to maintenance and distribution, the Spanish government set these tariffs, reducing profitability and delaying the payback period of such investments.

1.2.2.2. Spanish current regulatory framework

In October 2018, the government wrote a new RD that completely changed the regulatory framework regarding renewable energy. Most important changes were the abolishment of the “Sun tax” and eliminating the limit for installed capacity, previously set at the contracted power, with the objective of propelling the development of renewable sources of energy.

The first months saw few projects signed, as uncertainty still covered the sector. However, as 2019 started, optimism is on the rise and it looks like the market for photovoltaics in Spain is going to experience a surge.

The purpose of the last RD is to complement its predecessor, defining necessary aspects of the matter, allowing for the transition towards a renewable energy market.

An overview of some important definitions regarding the RD 244/2019 can be seen bellow:

- Self-Consumption: Energy consumption by one or more users from near or associated sources of energy. Two different sorts are defined:
    - Without excess: No spillage of energy to the grid, which is ensured with an anti-spillage system.
    - With excess: Excess energy can be injected into the grid. It can either include remuneration or not. For a system to be within a remuneration scheme, it must check the following requisites:
        - Renewable primary energy source
        - Maximum installed capacity of 100kW
        - Signed contract for the compensation of excess

  Self-Consumption can also be classified by consumption:
    - Individual
    - Collective: series of consumers associated to the system and scheme
- Grid connected installation: A generation installation connected to the grid directly, or an isolated system that has the possibility of connection via switches.
- Isolated installation: A generation system that cannot be physically connected to the grid at any time, either directly or indirectly.
- Production systems associated or near to consumers: Systems generating for one or more consumers within the definition of self-consumption.
- Anti-spillage mechanism: Device/s that prevent any injection of energy into the grid.

In addition, the installed capacity for photovoltaic systems is defined as the maximum power for the inverter. Reading units with hourly timing must be installed for every installation, required to calculate pricing and tariffs.

Access and connexion permits must be included for all production systems, with exception of self-consumption without excess or with excess but with an installed capacity of 15kW or less.

Procedures and paperwork needed to install a PV plant for self-consumption are now explained:

- System design.
- Access and connexion permits: This is arranged with the Distribution Company and usually takes over ten days.
- Building license.
- Public or environmental and administrative authorisation: This depends on the site chosen.

- End of building and installation certificate: Handed to the autonomous community by the engineer in charge
- Initial and periodic inspections.
- Exploitation permit: Not needed for 10kW or smaller systems.
- Register in the Self-Consumption record: Not needed for 100kW or smaller systems.

On top of that, a series of contracts must be signed before starting to generate. Firstly, access and connection contract for power plant that make use of the distribution grid; not connected to an interior grid. This usually takes about two weeks. Secondly, an auxiliary services contract, not a case for PV installations. Thirdly, a compensation of excess contract. Only those systems for individual consumption without excesses are exempt of this, as collective consumption must agree on a distribution of the energy generated. Finally, and only for PV plants that are going to sell their energy to the grid, a representation agreement.

2. State of the art

2.1. Solar resource

In this section, basic concepts regarding the sun, geometry and angles are explained. These definitions will allow for better understanding of the PV simulations.

2.1.1. The Sun

The Sun is a plasma sphere with an effective temperature of 5777K. This value, also known as the black body temperature, is the temperature a black body of the same size must have to emit the same radiant flux density. Energy is irradiated from the Sun's surface into space, and travels through this heat transfer mechanism onto Earth.

It is defined as solar constant, G_{sc}, as the total radiation energy received on a perpendicular surface to the Sun's rays, per unit of time and per unit of area. Calculated at Earth's mean distance from the sun, it has a value of 1367Wm^{-2}.

Due to Earth's orbit around the Sun, the distance between both is not constant throughout the year. Earth is closest to the Sun on the Periapsis, 3rd of January, and furthest on the Apoapsis, 3rd of July.

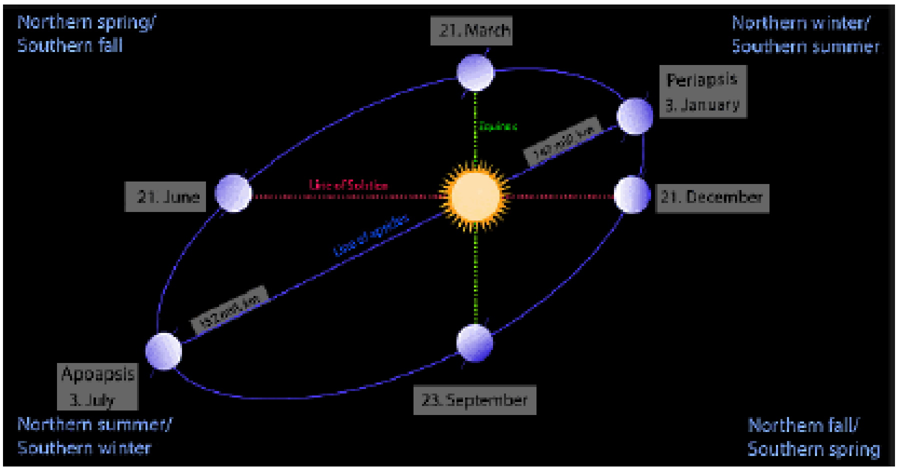


Fig 2-1. Earth's orbit around the Sun through one year. Adapted from [6]

For a chosen day of the year, n, irradiance can be approximated using equation (2-1):

$$G = G_{sc} * \left(1 + 0.033\left(\frac{360}{365}n\right)\right) \tag{2-1}$$

2.1.2. Solar geometry

Basic concepts regarding solar geometry are explained:

- Latitude and longitude: Coordinate scheme of angles that define points on a sphere, in this case Earth. Latitude uses Earth's equator as reference, and defines the angular distance north (positive) and south (negative), of a point. Longitude refers to the angular distance of a point east (positive) and west (negative) from the Greenwich meridian. Both are measured in degrees and minutes.
- Solar azimuth angle, Υ_s: Is the angle between Suns' rays observed from the horizontal plane and the true south (Northern Hemisphere). Angles to the east are negative and to the west positive.
- Surface azimuth angle, Υ: Angle between an imaginary line pointing out of the surface and true south. Again values to the east are negative and will equal zero if the panel is facing south.
- Solar altitude angle, α: Angle between incoming Suns' rays and a horizontal plane. This value is maximum in summer solstice and minimum in winter solstice.

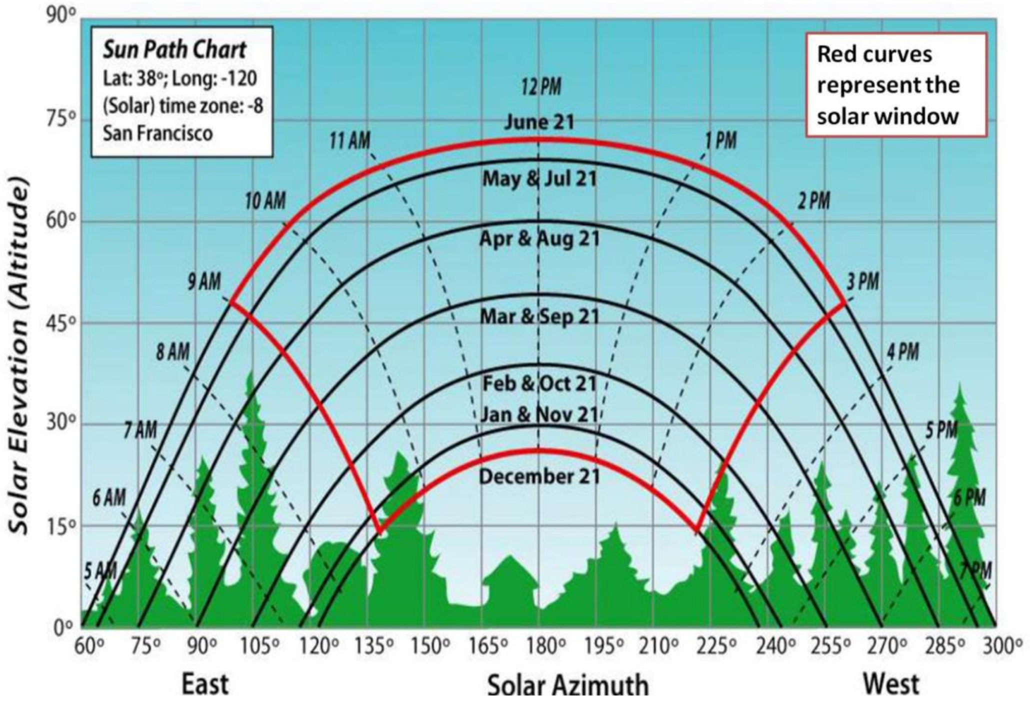


Fig 2-2. Solar elevation throughout the year. Adapted from *[7]*

- Tilt angle, β: Angle between the panel/ collector and the horizontal.
- Zenith angle, ϑ_z: Angle between an imaginary line pointing to the sun and the zenith (vertical). At sunrise and sunset, the angle is 90º. Sum of altitude and zenith angles equal 90º.
- Incidence angle, ϑ: Angle between incoming Suns' rays and the normal of the surface.

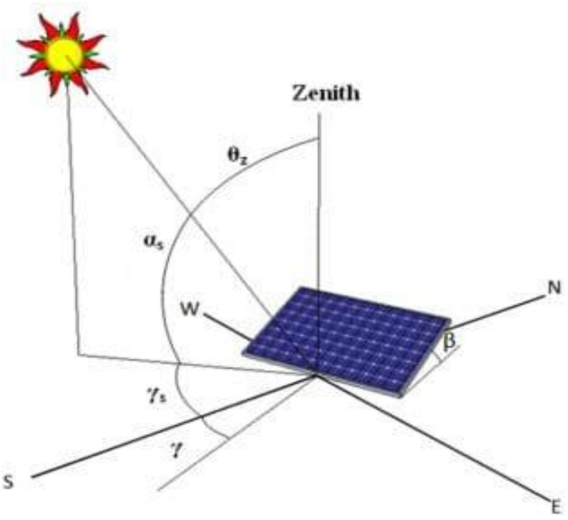


Fig 2-3. Solar angles. Adapted from [8]

2.1.3. Solar concepts

Fundamentals of solar irradiance are now explained:

- Photon: Massless particle of electromagnetic radiation.
- Irradiance: Energy per unit of time on a unit area, W/m^2.
- Irradiation: Energy on a unit area, J/m^2 or kWh/m^2.
- Solar radiation: Flux of photons coming from the Sun.
- Direct Normal Irradiance or Beam (DNI): Solar radiation per unit area perpendicular to the rays of the sun, without scattering and coming directly from the Sun.
- Diffuse Horizontal Irradiance (DHI): Solar radiation per unit area after scattering, hence its direction has been changed and does not come directly from the Sun.
- Global Horizontal Irradiance (GHI):

$$GHI = DHI + DNI * \cos(\vartheta_z) \qquad (2\text{-}2)$$

2.2. PV systems

PV systems consist of PV arrays, inverters and, in some cases, a battery bank to store the excess energy. In this section a summary of its components, working principle and important parameters is given.

2.2.1. PV array

2.2.1.1. Components

A PV cell, or solar cells, is a unit that transforms solar energy into electrical energy. A set of solar cells connected together electrically to generate a desired power at a precise voltage and current is called a PV module. Modules also have protections to avoid damage to the cells from the environment and protect operators. By connecting modules in series, you create a string. A set of strings in parallel is called a PV array. By increasing the amount of modules per string, you increase the voltage of the array. On the other hand, if you increase the amount of strings in the array, you will increase the current. PV panels have a lifetime of around 25 years, which is the usual analysis period of PV systems.

An example of a cell, a module, a string and an array can be seen bellow.

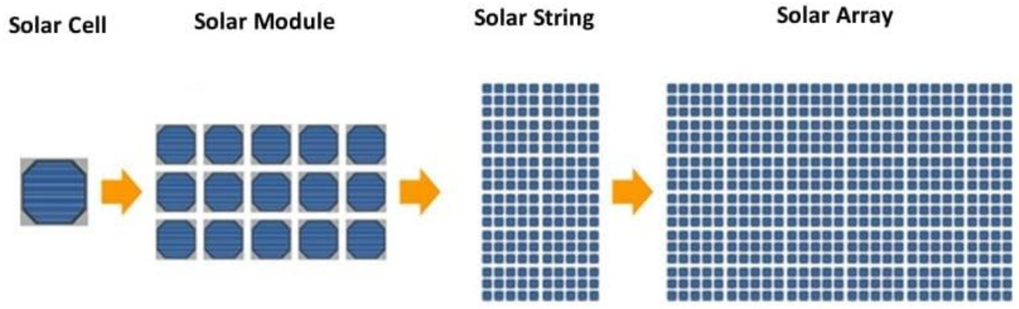


Fig 2-4. PV cell, module, string and array [9]

2.2.1.2. Working principle

Solar cells are semi-conductors. The most common material used is silicon. When a silicon atom is replaced by a 5 valence electron atom, such as phosphorous, an n-type material is obtained and when it is replaced by a 3 valence atom, such as boron, a p-type. By combining these two, we get a PN junction, where the extra electron from the n-type silicon will move to fill the “hole” from the p-type, forming an electron-hole pair. Because of this, the n-type becomes positively charged and the p-type negatively, creating an electric field in the cell.

When a light photon strikes silicon, its energy is absorbed by a loose electron, which comes off the atom and will follow the electric field generated thanks to the PN-junction. The junction is connected in series with an external load, resulting in current being generated.

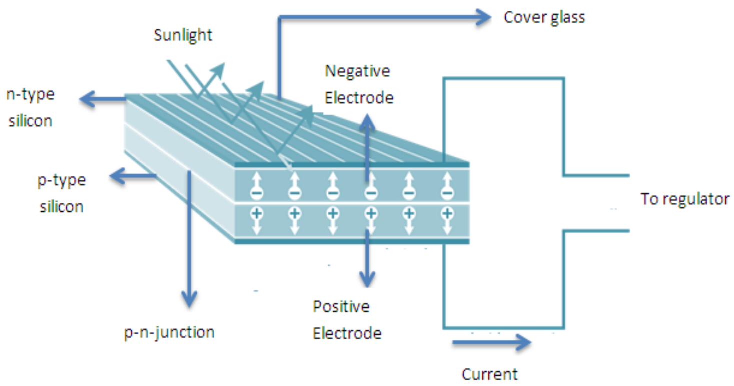


Fig 2-5. PN-junction. Adapted from [10]

2.2.1.3. PV cell characteristics

A cell can be described like a diode and can be approximated to the model seen in figure [2-7].

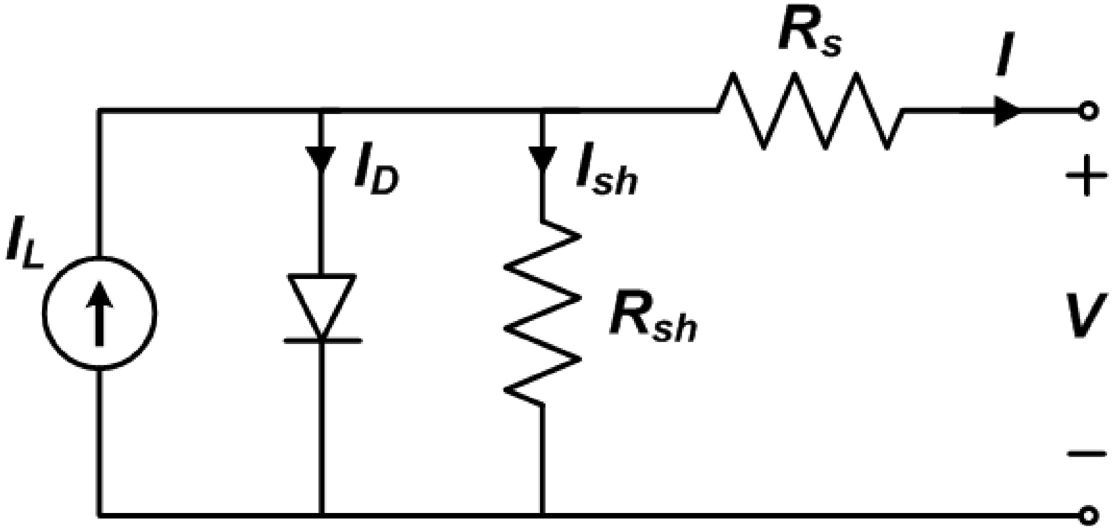


Fig 2-6. Single diode model for PV cells. Adapted from [11]

With losses being accounted for with the resistances, one in series for voltage and one in parallel for current. The resultant ideal current, supplied to the load, would be:

$$I_l = I_{pv} - I_d - I_{sh} \tag{2-3}$$

Where I_l is constant and I_d is the diode or dark current:

$$I_d = I_0\left(exp\left(\frac{eV}{kT_C}\right) - 1\right) \tag{2-4}$$

I_0=dark saturation current (A)
V= voltage across the cell (V)
e=electron charge (J/V)
T_C=Temperature of the cell (ºK)

Plotting current and power against voltage drop across the load we obtain the characteristic IV curve of a cell, figure [2-7]. This curve is crucial understanding the behaviour of a PV cell, which is heavily affected by irradiance and temperature.

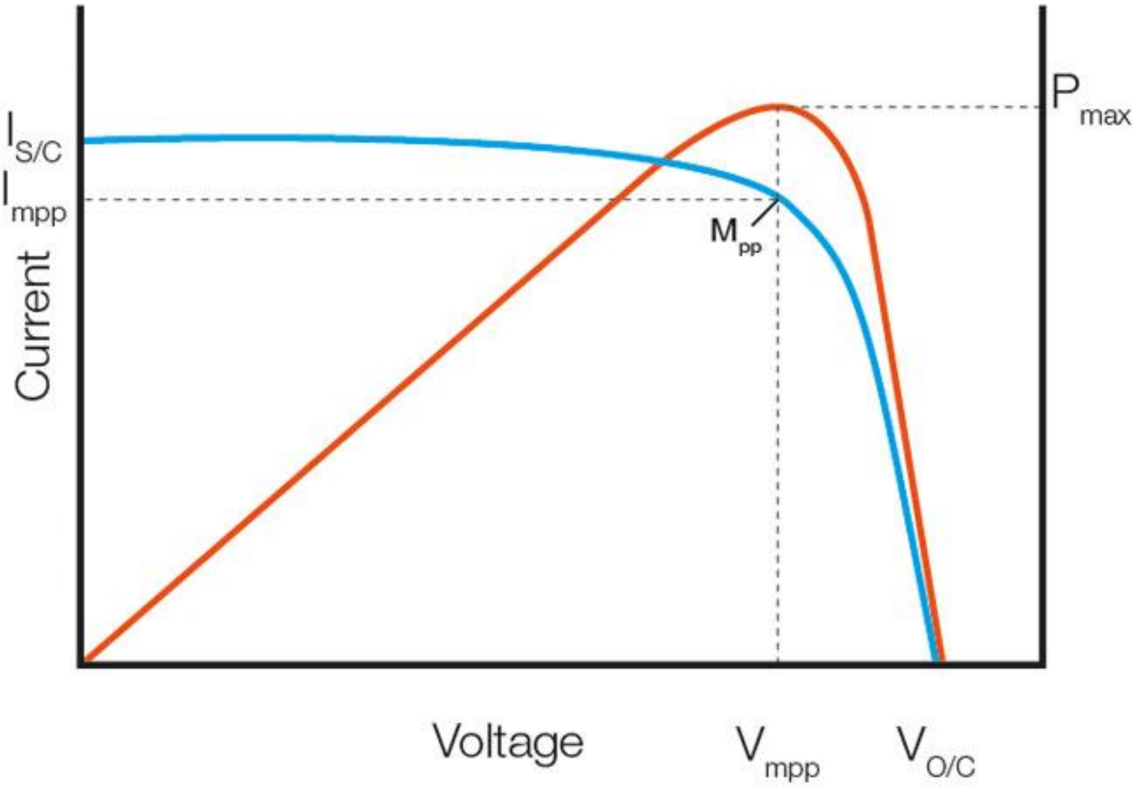


Fig 2-7. IV for solar cells. Adapted from [12]

In the above figure, the characteristic IV curve is displayed. It is important to note that the dependence of current on irradiance. As irradiance falls, so will current, as will the maximum power output.

2.2.1.4. Electrical parameters

Concepts regarding the operation of a cell and its behaviour are now explained in this section:

- Maximum power point: It is the operating point of the cell where the maximum power, P_{MAX}, is generated.
- Open circuit voltage, V_{OC}: Corresponds to the voltage across the cell when such is connected to an infinite resistance while receiving irradiance. It is the maximum voltage the cell will achieve.
- Short circuit current, I_{SC}: Corresponds to the current in a cell when operating without resistance (short-circuit). It is the maximum current a cell will experience.
- Standard Test Conditions, STC: The set of conditions used to test all PV panels, ensuring an equal comparison among them. These are:
    - Irradiance = 1000 W/m^2
    - Cell temperature = 25ºC
    - Winds speed = 1 m/s
    - AM: 1.5
- Electrical conversion efficiency, η: Evaluated under STC conditions. The ratio between electrical power generated by a cell and incident irradiance on it.

$$\eta = \frac{I_{MPP} * V_{MPP}}{G * A} \tag{2-5}$$

- Fill factor, FF: It corresponds to the ratio between the maximum power achieved in a cell and the product of the short circuit current and open circuit voltage.

$$FF = \frac{I_{MPP} * V_{MPP}}{I_{SC} * V_{OC}} \tag{2-6}$$

- Nominal operating cell temperature, T_{NOC}: Temperature of the PV cell operating under the following conditions:
    - Irradiance = 800 W/m^2
    - Cell temperature = 20ºC
    - Winds speed = 1 m/s
    - AM: 1.5

2.2.1.5. Losses

The main losses related to PV modules are explained bellow.

- Temperature loss: Not all irradiance is absorbed by the cell, and then transformed into electrical energy. Some gets lost as heat, via conduction, convection and radiation. The higher the temperature of the cell, the bigger the temperature difference with ambient, hence the greater the thermal loss will be. Thermal losses can be accounted for with the loss factor Υ_T. The effect this factor has on efficiency can be seen in equation 1234, with η_0 as the efficiency of the cell at nominal temperature (25ºC).

$$\eta = \eta_0 * \left(1 - \Upsilon_T(T_{cell} - 298K)\right) \tag{2-7}$$

- Soiling loss: As PV panels are placed outdoors, one can expect them to get covered with dust and other dirt. This will reduce the amount of irradiance received by the module. The degree of soiling depends on the location of the system, but can amount to monthly losses of 25%.
- Mismatch loss: These are caused by the way modules are connected with one another. Modules will experience different conditions, causing the electrical parameters to vary significantly. Power loss due to mismatch depends on circuit configuration, operating point of the module and the amount of different parameters with respect to the rest of the modules.
- Shading loss: Considered a mismatch loss, the shading of one panel will affect severely the performance of the whole string of modules connected. The effects of shading will be analysed in detail later.

2.2.1.6. Efficiency

One of the biggest constraints of PV is its efficiency. Solar panels efficiency has been limited to 24% in monocrystalline cells, tested under STC conditions. In table [2.1], it can be seen different types of cell ranked from highest efficiency (and cost) to lowest.

TABLE 2-1. PV CELL EFFICIENCY

Cell	Laboratory efficiency	Real efficiency
Monocrystalline	24%	15-18%
Polycrystalline	19-20%	12-14%
Amorphous	16%	<10%

The main problem with cell’s efficiency is its physical conversion. In 1961, a physical theory was proved, stating that the maximum possible efficiency in a photovoltaic cell with a PN-junction is limited to 33.7% [13]. This limit was known as the Schokley-Queisser limit.

2.2.1.7. Partial shading in PV cells

Shading in such systems can be due to clouds, buildings and trees among other. A direct correlation exists between current and irradiation under uniform values. For higher values of irradiance, bigger currents will be generated. However, non-uniform shading means more complex situations, because they vary throughout the year as sun’s position changes and the source of the shading changes.

Once a cell in a module is shaded, the power drop experienced in the module will be proportional to the percentage of shaded module. In other words, as cells are connected in series to form a module, shading one cell means less current flows through all of them, hence reducing the power output. This effect can be seen in figure [2-8].

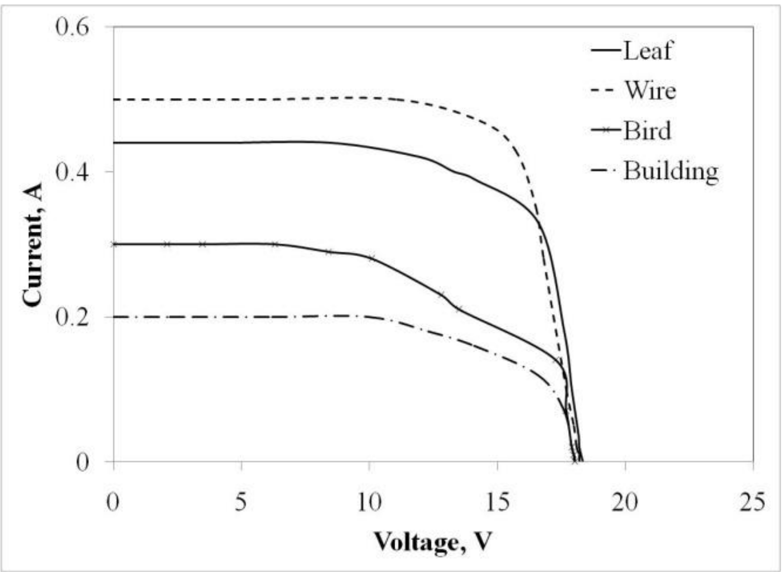


Fig 2-8. Effect of different shading elements on IV curve. Adapted from [14]

If one cell is shaded and the current generated by such module drops, the whole string of modules connected will experience the same effect. Because of this, shading losses must be accounted for in preliminary studies to avoid PV system’s generation being heavily diminished.

2.2.2. Inverter

Solar panels generate electricity in DC (direct current). Electricity is transported (grid) and consumed in houses in AC (alternating current). Therefore, energy generated in PV systems must be transformed into AC via power electronics. The device used is an inverter. It must fulfil a series of characteristics to ensure a correct operation: synchronisation with the grid (240V and 50Hz in Europe) to allow injection of energy, interaction and variation depending on demand and disconnect from the grid if a major error occurs. Inverters are usually changed every 8 years and its efficiency surpasses 95%.

2.2.2.1. Working principle

Once a DC input current is fed to the inverter, a series of electronic devices switch such current and invert its polarity. This produces a square wave. Pulse Width Modulation (PWM) is used, in PV, to turn this square wave into a sinusoidal wave, so it can be fed to the grid. PWM consists of generating DC voltage in the form of pulses of different width; bigger width for bigger amplitude of the sinusoidal wave. These pulses are then averaged to achieve the sinusoidal wave.

To smoothen out the wave and make it sinusoidal, passive filters are used, consisting of inductors and capacitors, whose task is to soften current and voltage respectively.

Figure [2-9] is the output voltage of a PWM inverter for a whole period. At peak voltage for the sine wave, it can be observed pulses of larger width in the square wave.

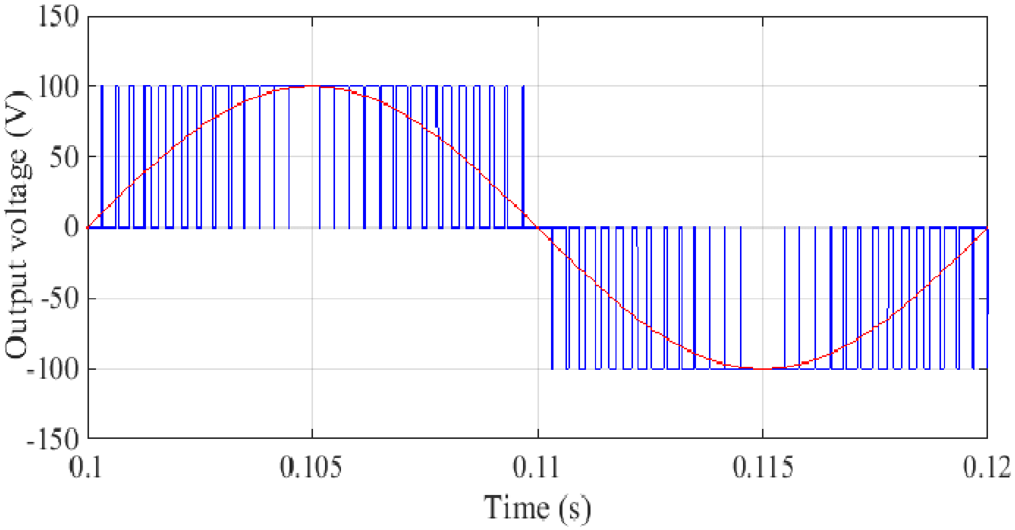


Fig 2-9. Square signal and sine wave output. Adapted from [15]

2.2.2.2. Inverters in PV:

Inverters must be chosen wisely depending on the PV system. The selection is conditioned by the panels' characteristics; maximum power point (power, current and voltage), open circuit voltage and short circuit current, and the desired DC/AC ratio. In addition, it must be decided the type of inverters to use:

a) Central inverter: Inverter is connected to a full array of panels. Best for large power systems. Central inverters have the biggest efficiency of the three.
b) String inverter: One inverter per string of panels. Cheapest of the options, and easiest for maintenance. However, if a module experiences performance problems, the whole string will go down, and the inverter.
c) Module inverter: Each module has its own inverter, with lower nominal power than the other two. With this type of inverters, if a module is partially shaded, only that module will see its power output reduced. However it is the most expensive of them all and maintenance might be difficult if panels are not easily accessible.

In figure [2-10] a display of all types of arrangements can be seen. Case (d) is a central inverter with DC optimizers. A DC optimizer, only used in grid-tied systems, is a DC/DC which allows to control the power output of modules. Hence, if one module is underperforming, it will not affect the rest of the string.

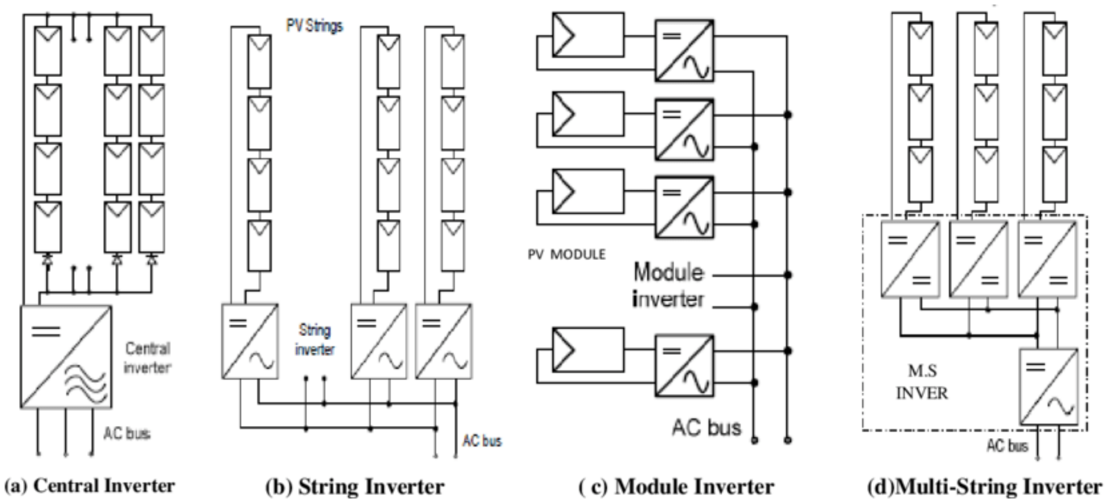


Fig 2-10. Types of PV inverters. Adapted from [16]

2.2.2.3. Maximum Power Point Tracking, MPPT:

As mentioned before, every panel has a maximum power point. This varies with solar irradiance and cell temperature. Obtaining this value from every system is a key issue in inverters, and that is where MPPT comes into play. With the use of an algorithm that controls voltage by changing the load, inverters can adjust to obtain the maximum power output from panels depending on the conditions it faces.

Partial shading will also give different values for current, affecting the operating conditions of strings at a certain irradiance.

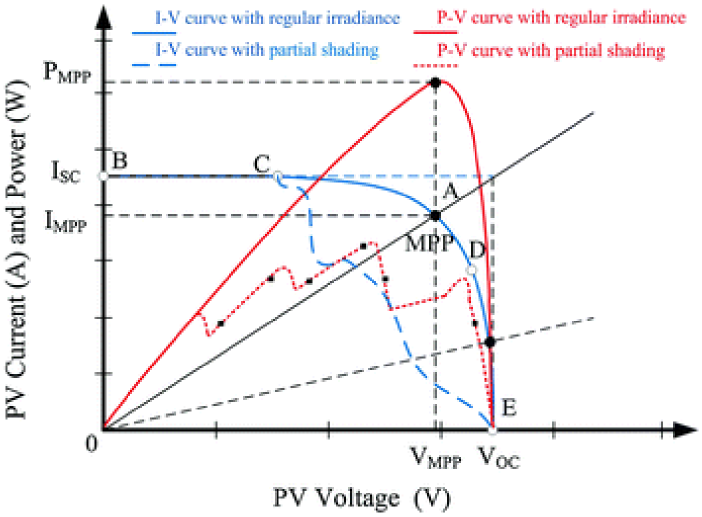


Fig 2-11. MPPT for a module under partial shading. Adapted from [17]

2.2.3. Batteries

Batteries are a form of energy storage through electrochemistry. In PV systems, batteries are connected to charge when generation is bigger than demand and to discharge when generation cannot meet demand. This maximises the solar resource exploitation as higher renewable penetration as less energy is injected into the grid, which in non-remuneration cases would mean losses.

The most common type of batteries in PV are lead-acid.

2.2.4. Connexion and operation

First, the desired current and voltage must be chosen. Secondly, modules will be connected in series to adjust to the selected voltage, and in parallel for the current.

- Parallel connexion, n_p: Total current will be the addition of currents coming from each string, or parallel. Voltage will be equivalent to the voltage of a single parallel.
- Series connexion, n_s: Current is limited to the minimum generating module (due to shading as state before). Voltage will be determined by adding voltage of each module.

To calculate the total number of modules: $n_{tot} = n_s * n_p$

The final electric parameters of our system will be:

- $I_{tot} = I_{string} * n_p$
- $V_{tot} = V_{modules} * n_s$
- $P_{tot} = V_{tot} * I_{tot}$

To protect the system and optimize generation, a series of electrical elements are used:

- Bypass diode: Connected in parallel to each module, allowing current to flow through diode if panel is shaded and its current drops. This ensures that if a module's output current is reduced, it does not drag the rest of the string down.
- Blocking diodes: Installed in series to a group of modules to erase losses related to current backflow (night-time) and short circuits.

Figure [2-12] shows an example of the previously described configuration.

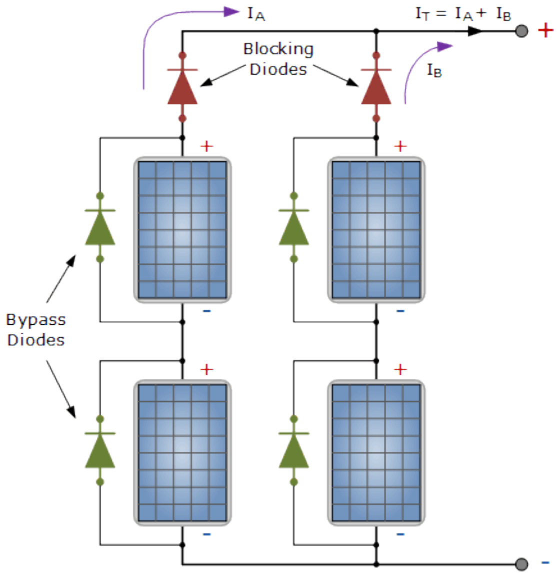


Fig 2-12. Array layout with blocking and bypass diodes. Adapted from [18]

2.2.5. DC/AC ratio

With the total DC capacity and the inverter(s) AC capacity, the DC/AC ratio is calculated. This value is of extreme importance when sizing a PV system. If a system is designed with a DC/AC ratio higher than one, in peak production hours the inverter will limit AC energy generated by "clipping" power converted to avoid damage.

On the other hand, if a DC/AC ratio lower than one is chosen, all energy generated by the panels will be transformed in AC but the inverter will be oversized, meaning costs will be higher and less energy will be finally generated.

As mentioned before, a module's lifetime is around 25 years, however in this period its power production declines; around 2-3% on the first year and then approximately 0.5% the next years. By choosing a ratio above one, it could ensure that throughout its lifespan the PV system will never become undersized. In addition, energy harvest will increase.

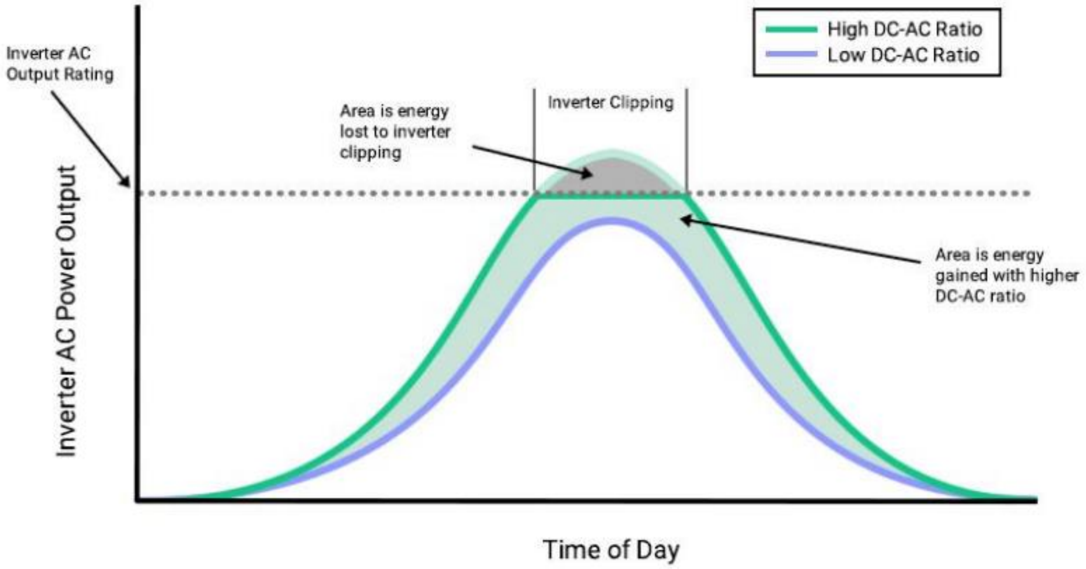


Fig 2-13. Energy production of a PV system with different DC-AC ratios. Adapted from [19]

In figure [2-13] a comparison of two different DC/AC ratios can be seen. The horizontal dotted line is the inverter's AC power, and the blue/green line is the energy generated by the array. This last line will reduce as years come by due to degradation. The extra energy harvested is the area between the blue and green lines.

A ratio of around 1.2 was chosen for this project as it allows that mentioned extra energy to be generated, but also as panels degrade, the ratio will come closer to unity but not below, reducing clipping losses.

2.2.6. Performance ratio and capacity factor

Performance ratio is a quality measure of a PV plant. It shows the ratio of AC energy generated to the theoretical energy the system could generate. Therefore, this value allows the comparison of different PV plants.

The performance ratio depends on the efficiency of both panels and inverter(s), losses mentioned in section [2.2.1.5] and environmental factors like irradiation and temperature. Accepted values for performance ratio range from 0.6 to 0.8.

The capacity factor of a power plant is defined as the ratio between energy generated over a period to the maximum energy output possible over the same period:

$$CP = \frac{E_{gen}}{P * t} \tag{2-8}$$

Capacity factor for PV plants take values of 10-25%. Renewable energy sources tend to have lower CP due to the dependence on sun, wind, etc. In solar energy, capacity factor is even lower because there is no generation at night. The fraction of yearly hours when a PV system generates electricity is analysed later.

3. Methodology

Energy consumption and PV generation will be analysed for seven different cases, plus two extra with batteries. These cases differ in load, installed capacity and regulation scheme. A general overview of the project budget will be developed, with a comparison of load and production throughout three years.

For each scenario, a series of key values will be calculated: renewable fraction (the percentage of demand covered by the generation unit), amount of energy injected to the grid and NPV.

Demand for each campus will be used in the project. Data from the three main campuses will be compared (Leganés, Getafe and Colmenarejo), important percentiles will be calculated, as well as peak values and distribution.

In addition, different PV simulation programs will be compared; PVSyst and SAM. The objective is to note similarities and discrepancies of both programs to serve as a reference for future work. Furthermore, if the decision of installing panels in both Leganés and Colmenarejo is taken, a more accurate estimate can be drawn, as the more experimental results, or simulations, the more accurate results one may retrieve. PV simulation of 25 years will be performed as it is a usual lifetime for such projects.

3.1. Location for PV systems

Two UC3M’s campuses are chosen for the PV and demand analysis; technical campus of Leganés (latitude of N40º 33’ and longitude O3º 76’) and campus of Colmenarejo (latitude of N40º 54’ and longitude O4º 01’), both in the Community of Madrid.

For Leganés, four buildings will be covered in panels: Betancourt (building 1), Torres Quevedo (building 4), Juan Benet (building 7) and the Alfredo di Stephano sports centre.

For Colmenarejo, three buildings; the cafeteria, the library, the student village, and two land plots have been deemed appropriate.

Fig 3-1. Rooftops in campus of Leganés, UC3M (Google Earth Pro)

Fig 3-2. Rooftops and plots in campus of Colmenarejo, UC3M (Google Earth Pro)

Figure [3-1] and figure [3-2] are images made with Google Earth Pro showing the available areas for panel installation. In blue, the rooftops and in red the land. In green there is a hypothetical case where the university grants permission to install panels in the middle of the campus. This is very unlikely, however it will be considered to see how much extra capacity can be installed.

3.2. Load

UC3M is composed of a total of five campuses; Leganés, Getafe, Colmenarejo, Puerta de Toledo and the Technology Park. Year consumption of all campuses for 2016 was approximately 15GWh.

Most of the energy is consumed by the first two mentioned and around 10% by the other three. Figure [3-3] shows the percentage of energy consumption by each campus.

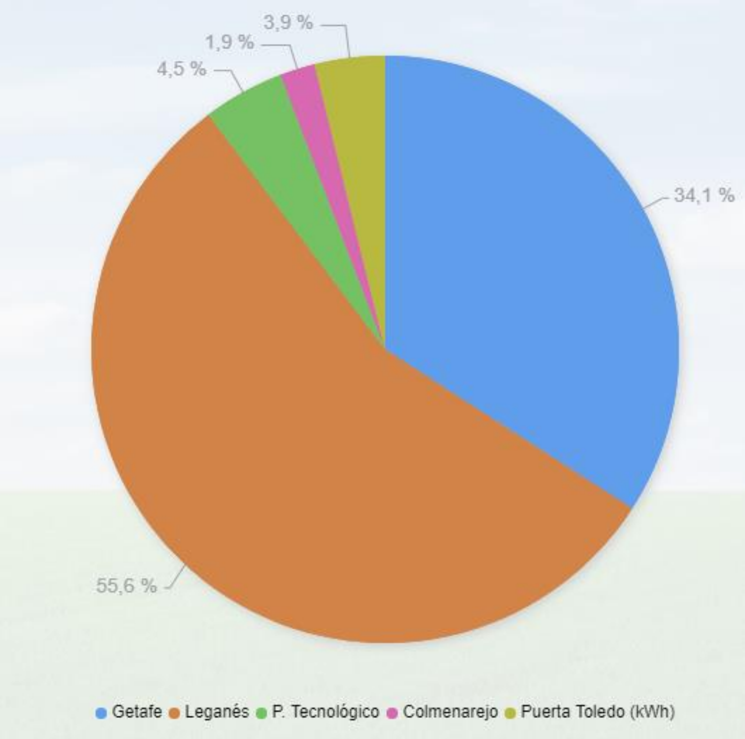


Fig 3-3. Demand distribution in UC3M

To obtain the demand curve for the campuses throughout 2016-2018, the three years chosen for the analysis, different sources had to be used. 2016's data was obtained from the Treasury Department's webpage [20]. However, the rest of the data could not be found there, and was downloaded from a data platform used by the maintenance department of the university.

Here, consumption was split into different transformers and buildings. First they were added up to calculate demand per building, and then the aggregate demand for each campus. In figure [3-4], transformers for building 4 in Leganés, Torres Quevedo, can be seen. This platform consisted of a remote desktop, which worked slowly, making the task longer than it should be.

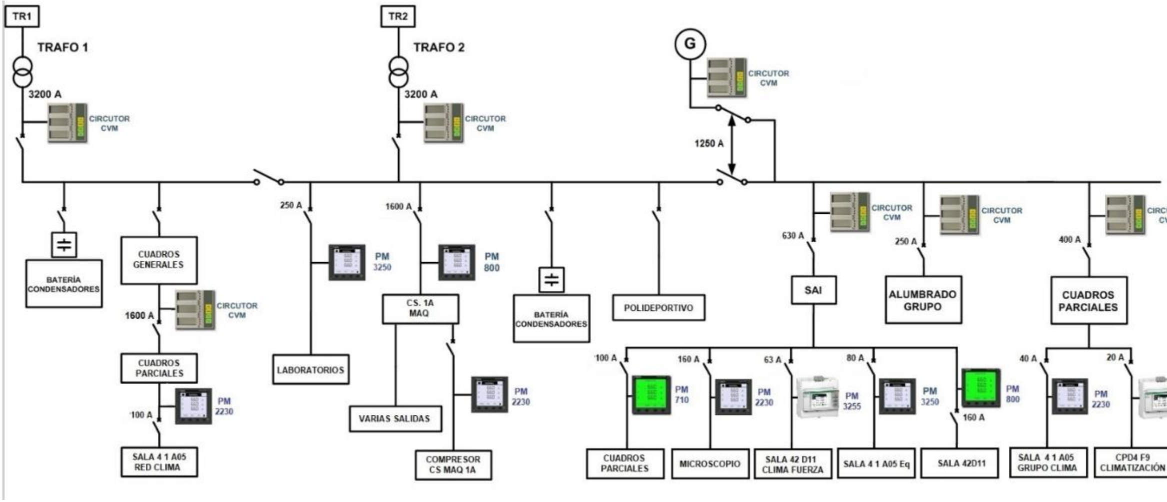


Fig 3-4. Electric circuit for Leganés' buildings

In such data retrieved, errors and mistakes were found all over for Colmenarejo, as specified by the responsible of the Department of Energy Efficiency. Those errors were caused by the different data system used in Colmenarejo, compared to Getafe and Leganés. These faults were empty data sections in the record, some negative values or sudden spikes to values of TW consumed in one hour. 2017's and 2018's demand curves for Colmenarejo were finally retrieved from the company working with the department.

Figure [3-5] shows a plot done on Matlab of the load time series for the two selected campuses, Leganes and Colmenarejo, during 2016.

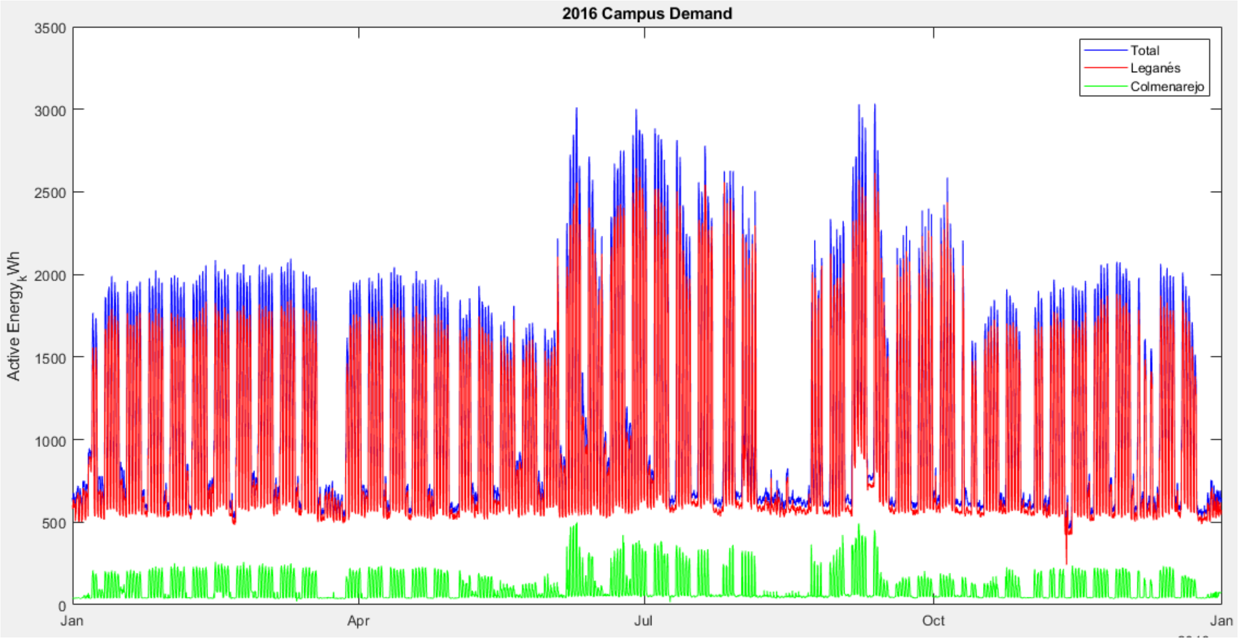


Fig 3-5. Demand for Leganes and Colmenarejo in 2016

Looking at the graph, it can be observed that load reaches its maximum in September, at the beginning of the academic course, and has above average values during exams and the beginning of summer vacations. Lowest values can be found during holidays, like Christmas and new year's (January), summer (August) and holy week (end of March). Week patterns can be seen too, as load shows similar values for five days in a row and then drops for two consecutive years.

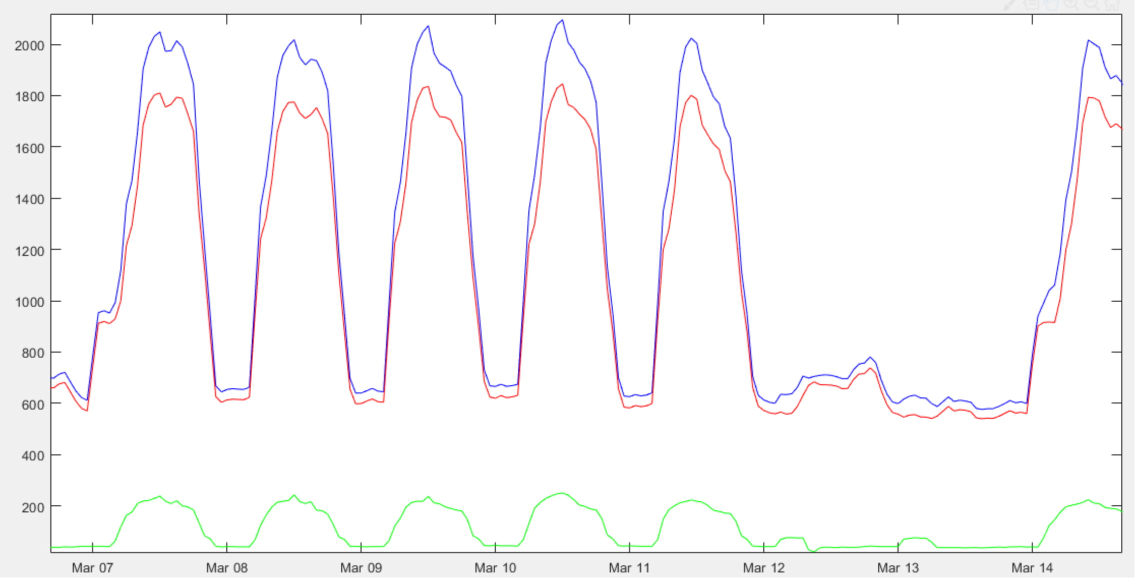


Fig 3-6. Weekly load for both campuses

Annual consumption for the campus of Colmenarejo is 858.5MWh and for the campus of Leganés 8.7GWh.

A series of changes have been made to improve energy efficiency on all campuses:

- Bulbs have been substituted for LEDs, which show a lower consumption.
- Climatology is controlled to reduce its use when unnecessary.
- Space usage has been optimised.

This has led to a reduction in consumption in major campuses. This drop can be seen in figure [3-7]. Despite Colmenarejo having an increase in consumption, this is not considered to be significant.

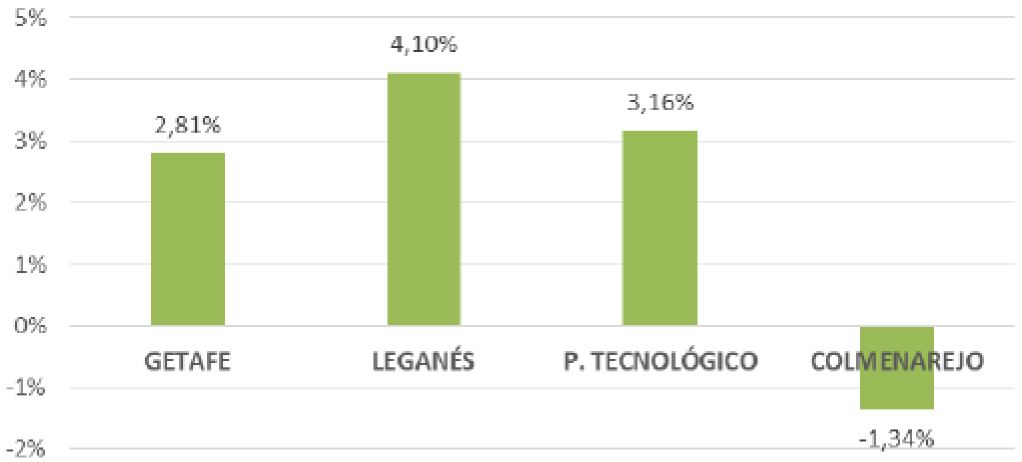


Fig 3-7. Energy savings from 2017 to 2018. Adapted from [21]

3.3. Generation

Both locations present favourable conditions for solar systems due to their solar irradiance and available surfaces. A PV system for all areas available will be set up, with fixed PV panels and optimum spacing and tilt. Current installed panels will be taken off, as they are old and such technology has improved since they were installed.

Solar potential analysis will be evaluated with System Advisor Model (SAM). It is a tool that focuses on performance and financial analysis and contains various models for the renewable energy sector.

The objective here was to maximise installed power, taking into account the shading the array would experience if placed in a certain location. This means that some places were not covered with panels as their daily irradiation would be too low. In addition, in the 3D tool the active surfaces, panels, were long rectangles with no space for workers to pass from row to row. A reduction of the number of panels was estimated to account for these spaces in the plots in Colmenarejo and other big systems installed.

Data retrieved from the simulations included energy generated for the chosen period hourly and yearly, economic information and performance and efficiency results. Degradation for panels was chosen to be 0.8% per year following the values found on SunPower's webpage [22].

3.3.1. SAM's Model Algorithm

SAM's model makes calculations for all 8760 hours in a year. A summary of the calculations can be seen below:

- Sun angles, nominal beam and diffuse irradiance on the plane of array and near-object shading factors are calculated according to weather files and user specifications.

- Reduced diffuse irradiance and self-shading DC loss factor for the specified plane of array.
- String voltage calculation
- Module model is ran, giving for a single module DC output power, module efficiency and temperature.
- Calculate array net and gross DC power according to the specified number of modules, strings and losses,
- Apply inverter’s sub model to obtain AC power and inverter efficiency.
- Subtract transformer and wiring losses, giving net AC power.

Further explanation of the steps can be found in [23].

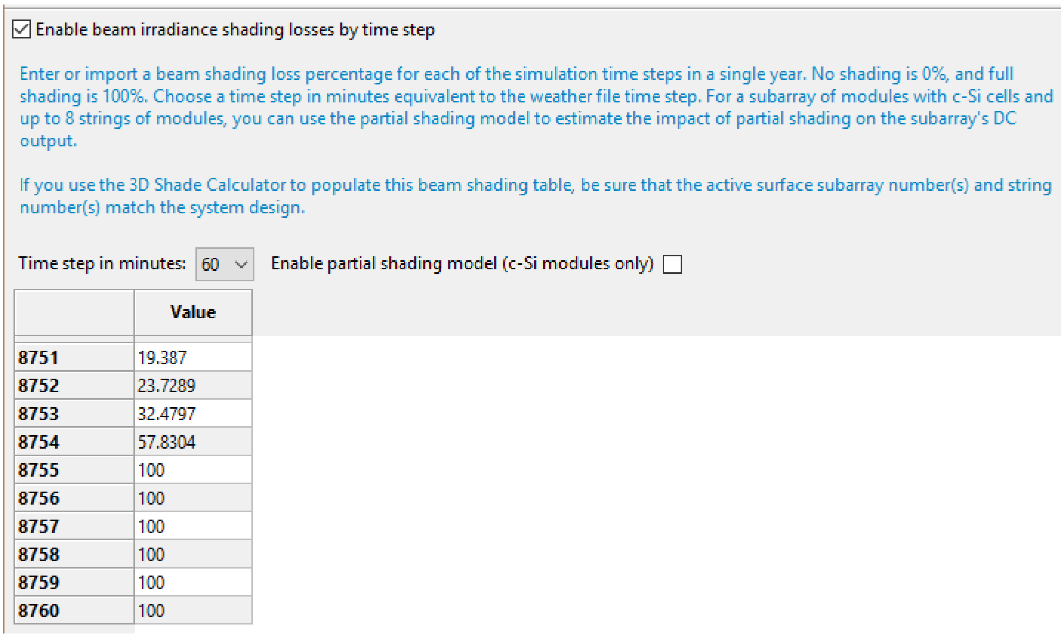
In addition to this, SAM includes parametric comparison, scripting and macros. Macros are premade scripts which allow user to optimise subarray layout or size its system according to different parameters.

3.3.2. Shading in SAM

Individual 3D files of the different buildings were designed with the help of Google Earth Pro, from where the geometry of the buildings was obtained. A 3D file for each campus, aggregating all buildings, was not used as the program had issues simulating the shading for all the elements and crashed during the process. Self-shading model was discarded as this only accepted squared areas and did not take into account near buildings or other elements that could shade the panels.

Once the 3D file was created, SAM calculated beam irradiance shading losses for every hour of the year, with values ranging from 0 (no shading) to 100 (fully shaded). On the other hand, for partial shading the model was limited to 8 strings. As the designed systems have more than 8 strings, SAM’s support team recommended me to omit such shading loss.

Figure [3-8] shows part of the time step for a simulated system and shading losses:



☑ Enable beam irradiance shading losses by time step

Enter or import a beam shading loss percentage for each of the simulation time steps in a single year. No shading is 0%, and full shading is 100%. Choose a time step in minutes equivalent to the weather file time step. For a subarray of modules with c-Si cells and up to 8 strings of modules, you can use the partial shading model to estimate the impact of partial shading on the subarray's DC output.

If you use the 3D Shade Calculator to populate this beam shading table, be sure that the active surface subarray number(s) and string number(s) match the system design.

Time step in minutes: 60 Enable partial shading model (c-Si modules only) ☐

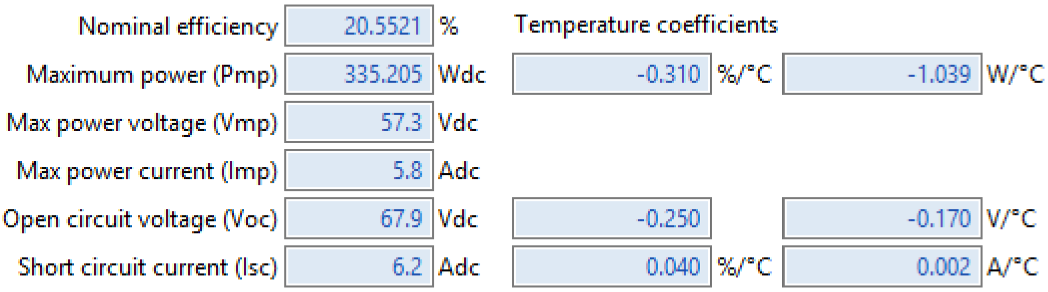
	Value
8751	19.387
8752	23.7289
8753	32.4797
8754	57.8304
8755	100
8756	100
8757	100
8758	100
8759	100
8760	100

Fig 3-8. Shading losses in SAM

3.3.3. System design

When designing a solar system, whether it is connected to the grid or not, the tilt and the distance between rows are key in obtaining maximum irradiance on the panels. First, a module must be chosen. Secondly, tilt must be calculated as it will affect shading on back rows; for a bigger tilt more distance between panels and vice versa. Thirdly, the distance from row to row. Panels will be set facing south.

For this project, module SunPower SPR-X21-335 was chosen for its efficiency and nominal power. Its dimensions are 1.559x1.046m.



Nominal efficiency	20.5521	%	Temperature coefficients			
Maximum power (Pmp)	335.205	Wdc	-0.310	%/°C	-1.039	W/°C
Max power voltage (Vmp)	57.3	Vdc				
Max power current (Imp)	5.8	Adc				
Open circuit voltage (Voc)	67.9	Vdc	-0.250		-0.170	V/°C
Short circuit current (Isc)	6.2	Adc	0.040	%/°C	0.002	A/°C

Fig 3-9. SunPower SPR-X21-335 parameters from SAM

Optimum tilt was calculated through a parametric analysis using SAM, where a number of inputs is chosen, tilt, and the output, DC energy, is computed. Panel tilt in Spain tends to have values of 30-35° for fixed structures. As tilt increased, so did energy produced, as the angle fits better for summer, when Spain receives more solar irradiation.

If our load was higher in winter, and hence we ought to produce more energy for such period, an angle that optimised production for those months would be chosen. Taking into account that the Sun's elevation in winter is lower, lowest in winter's solstice (21st of December), then panels should be set at a higher angle to improve production. The study at hand is about maximising yearly energy production, hence an angle is chosen for the highest energy output. The effect of tilt on monthly production can be seen comparing figure [3-10] and [3-11]. For a 35º tilt, energy production is higher for the months of May and June. On the other hand, for a tilt of around 70º, generation reaches its maximum in winter.

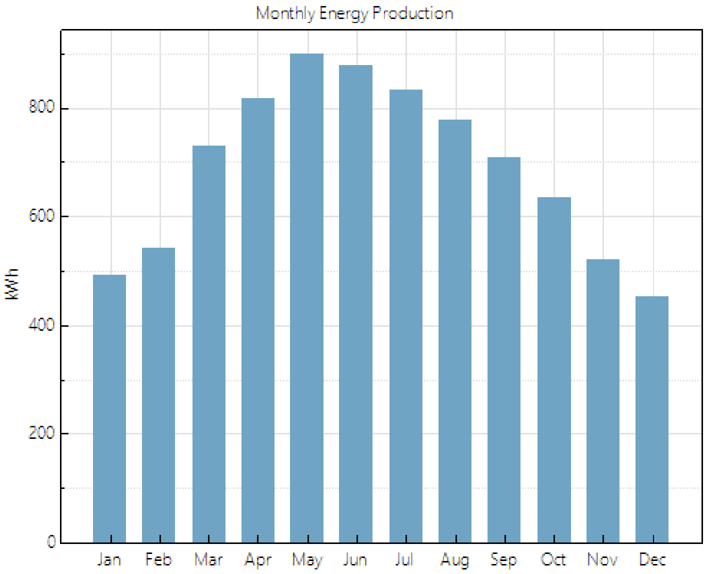


Fig 3-10. Month production with a tilt of 35º

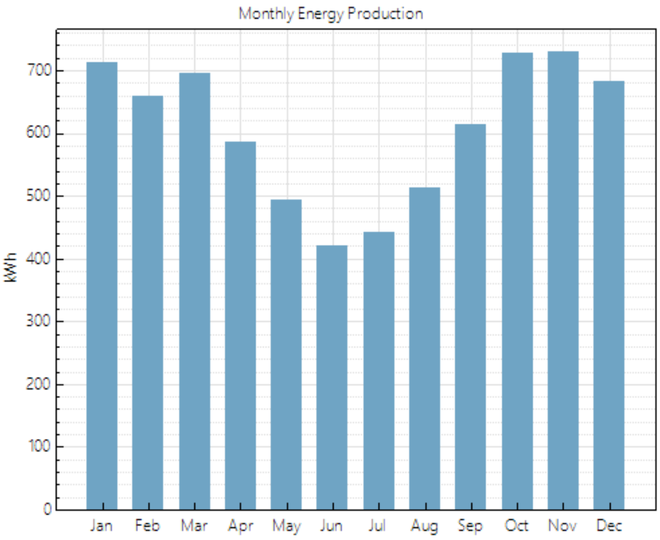


Fig 3-11. Month production with a tilt of 70º

Following the results from the parametric analysis, around 34º/35º the maximum annual energy was reached.

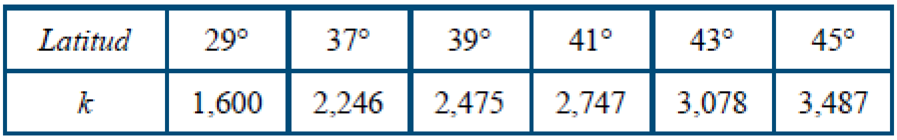
As tilt is increased, so does the distance between rows to reduce shading losses.

Following IDAE's technical specifications [24], the minimum distance between panels will be given by the formula:

$$d = h * k \tag{3-1}$$

With h as the height difference between the top of a panel and the bottom of the later and k given by table [3-1]. Measures and panels distribution can be seen in figure [3-12].

TABLE 3-1. VALUES FOR K VARYING WITH LATITUDE



Latitud	29°	37°	39°	41°	43°	45°
k	1,600	2,246	2,475	2,747	3,078	3,487

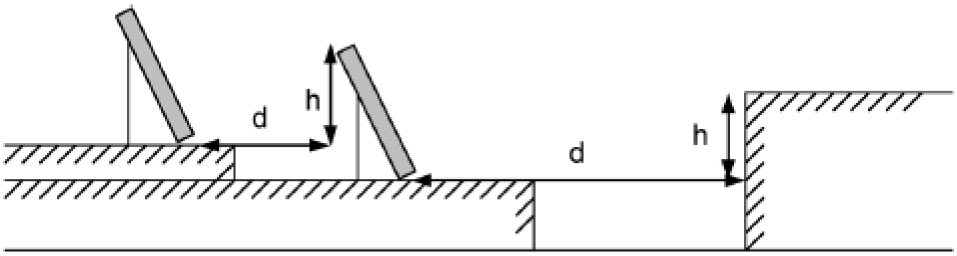


Fig 3-12. Module distribution

With a latitude of 41º and an h=0.89m, given by Pythagoras and panel's geometry, we get a minimum distance between panels of d=2.4m.

Once the amount of kWdc is calculated, multiplying number of panels by its nominal power, the inverter type and number must be chosen. The criteria used to select the inverter is explained in section [2.2.2.2]. Central inverters were chosen for the scenarios as they pose the highest efficiency.

3.4. Solar data

The two sources considered for the weather data; Meteonorm [25] and PVGis [26] are compared in this section.

Information regarding solar radiation, including direct normal and diffuse horizontal, latitude and longitude and elevation were obtained from both sources. The objective of analysing both is to see if significant discrepancies occur and to obtain an estimation of the solar energy the PV systems will receive.

In figure [3-13] global horizontal irradiance is plotted for both sources. Monthly averages are similar for most of the year. The biggest differences can be found for March, April, September and October.

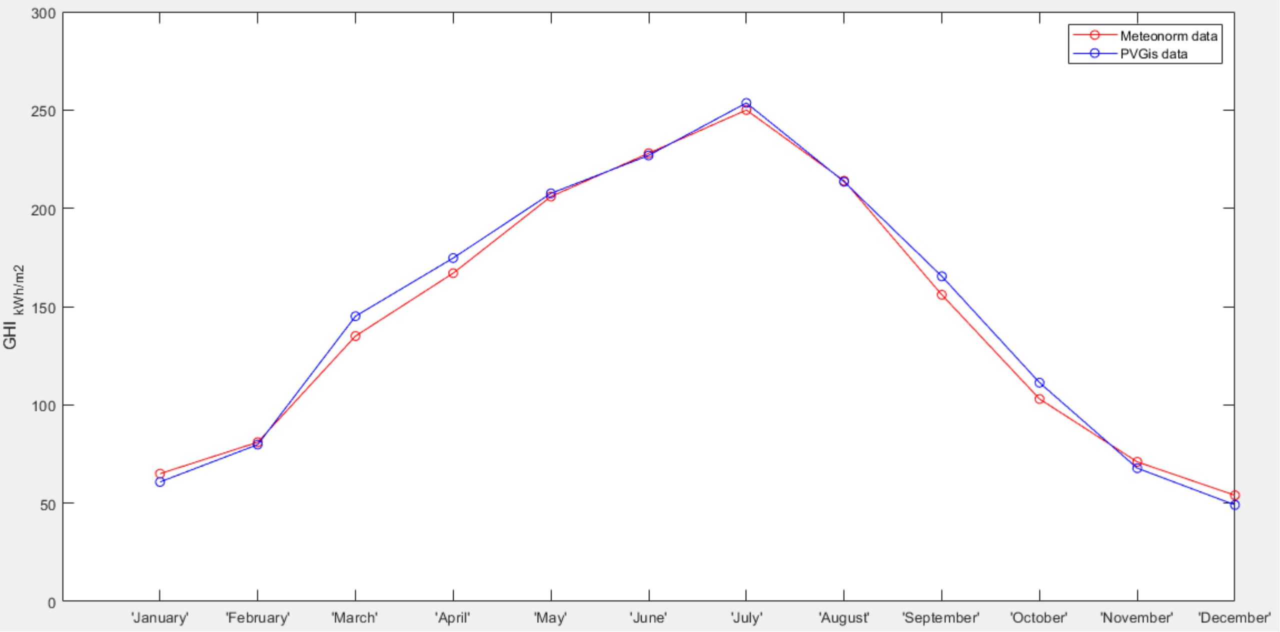


Fig 3-13. Monthly global horizontal irradiance for Meteonorm and PVGis

It was decided to use PVGis data source as it allowed for hourly data, whereas Meteonorm's Demo gave only monthly averages. Using hourly values would result in more accurate generation curves.

In figure [3-14], hourly global irradiance for Colmenarejo is displayed, with an annual average value of 4.76 kWh/m^{2}day.

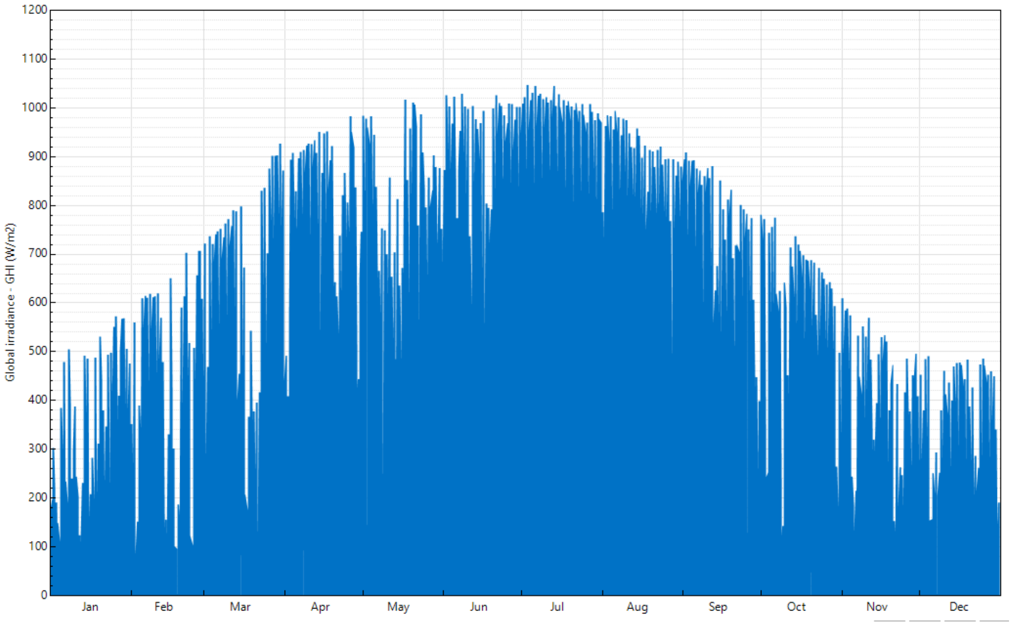


Fig 3-14. Global irradiance for Colmenarejo [PVGis]

Through summer, global irradiance is at its maximum value, whereas in winter, minimum values are found.

3.5. Statistic tools

To analyse demand data for both campuses various methods were used with Matlab, which are explained bellow.

3.5.1. Percentiles

A percentile is a useful statistic measure which compares a certain value with respect to the total pool. It indicates the percentage of data that lays below the chosen value or are equal to it. Percentiles 0,1,5,10,20,25,30,40,50,60,70,75,80,90,95,99,100 for energy injections and purchases will be calculated.

3.5.2. Boxplot and whiskers

Box plots visualise a sample of data with a series of important values. The plot will consists of a box, whose top and bottom are the upper and lower quartiles of the sample, respectively, or 25th and 75th percentiles. In addition, a red line inside the box will represent the median, or 50th percentile. Whiskers are added to the plot to represent the highest and lowest observations. Matlab's default whiskers length is 1.5 times the interquartile length. Values above or below whiskers are called outliers and are represented as red crosses.

This tool is especially useful when comparing two or more large sets of data, allowing to compare important values and spot anomalies.

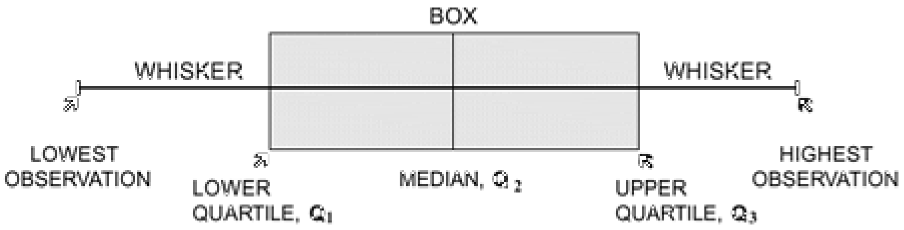


Fig 3-15. Box plot with whiskers. Adapted from [27]

3.6. Batteries

Batteries in this thesis are a work in progress; a simple energy analysis will be performed. The objective is to increase the share of energy generated that is consumed, however they will be approximated through a simple Matlab script that compares energy excess/shortage and battery charge and charges/discharges the battery consequently. This will reduce energy injection to the grid and purchases, as more excess energy from midday is stored and consumed when the system is not generating.

A range of values for the batteries' capacity will be chosen to see what percentage of the injected energy without batteries can be saved and consumed later.

4. Studied scenarios – Objectives and estimations

The different scenarios under analysis have been chosen to develop a full energetic estimation of the potential UC3Ms' campuses of Leganés and Colmenarejo of becoming energy sufficient, help reduce CO2 emissions and contribute in reaching the objectives set by the EU. In the campus of Getafe, a total of 160 modules, each of 220Wp, are already installed. The energy generated by such PV panels is being self-consumed by building number 18.

A definition of all scenarios, with the interest found in each of them, is given in this section.

4.1. Scenario 1: 100kW installed in Colmenarejo

The first scenario applies to Colmenarejo. With the objective of making income from the excess energy, 100kW will be installed. This capacity is the maximum allowed for a self-consumption system to be inside the remuneration scheme.
Taking into account the annual load, some excess energy could be expected.

4.2. Scenario 2: 100kW installed in Leganés

This scenario has the same objective as the previous one. However, no excess is expected from this case as annual demand for Leganés is around 8.7GWh.

4.3. Scenario 3: Maximum capacity installed in Colmenarejo

With this case a review of Colmenarejo's campus full PV potential is obtained. Surely generation will exceed demand, however this case may be interesting for future works as, in the future, peer to peer markets may appear. This would mean that individual generators may sell to other small consumers.

4.4. Scenario 4: Maximum capacity installed in Leganés

Leganés' potential is analysed in this case. Taking into account the demand at hand, full self-consumption most likely will not be achieved. This scenario will provide performance ratios lower than those from Colmenarejo, as all the systems are on rooftops, with higher buildings around, more shading will account for bigger power losses. Again this case is expected to prove more profitable if peer to peer markets develop.

From this scenario one can determine the possibility of full self-consumption for Leganés, which seems unlikely.

4.5. Scenario 5: Extra plot in Colmenarejo

The extra plot in Colmenarejo may allow us to install all panels without disturbing life at the university. This may also improve performance ratio, as with a total area of 33758m^2 all needed capacity may fit with spare space, allowing for more separation between rows, reducing shading. Capacity will be varied to achieve full self-consumption, making for a more realistic case with less excess. A final recommendation of the installed capacity needed for Colmenarejo will be made, taking into account the expected reduction of demand.

4.6. Scenario 6: Extra plot in Colmenarejo for both campuses

This case is based on the hypothetical scenario where regulatory framework is further modified to allow self-consumption to occur at a distance from the generating unit. Both campuses would be combined in an attempt to satisfy its demand through the entire PV system installed in the extra plot. Most likely, a close value for annual generation to demand will be obtained. Matching both generation and consumption will be attempted in this scenario.

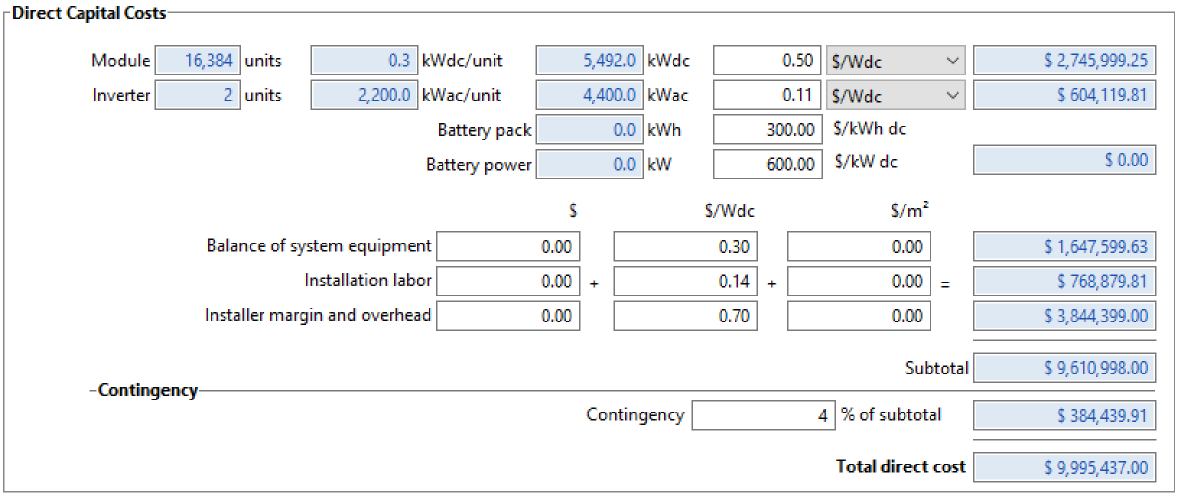
4.7. Scenario 7: Maximum capacity installed in both campuses

To finish off, this scenario is similar to the previous one, as demand for both campuses will be used. The difference will be that capacity will be maximised, using up all available space for both locations. With this result, it will be concluded whether both campuses can achieve full self-consumption. In addition, as grid injections are expected to be large due to all the capacity installed, a case with batteries will be studied.

5. Results

Final PV systems installed, demand analysis and different scenarios are explained in this section. Load and generation curves will be presented for the first year of the analysis, 2016, and important data for the next two will be displayed after.

Direct capital cost has been calculated through SAM’s system cost tab. Cost for PV modules and inverters, both in €/W, were obtained from [28], and were 0.5€/W for modules and 0.1€/W for inverters. The rest of the costs (installation and contingency) were left on default.



Direct Capital Costs

Module	16,384	units	0.3	kWdc/unit	5,492.0	kWdc	0.50	$/Wdc	$ 2,745,999.25
Inverter	2	units	2,200.0	kWac/unit	4,400.0	kWac	0.11	$/Wdc	$ 604,119.81
				Battery pack	0.0	kWh	300.00	$/kWh dc	
				Battery power	0.0	kW	600.00	$/kW dc	$ 0.00

	$		$/Wdc		$/m²		
Balance of system equipment	0.00		0.30		0.00		$ 1,647,599.63
Installation labor	0.00	+	0.14	+	0.00	=	$ 768,879.81
Installer margin and overhead	0.00		0.70		0.00		$ 3,844,399.00

Subtotal $ 9,610,998.00

Contingency

Contingency 4 % of subtotal $ 384,439.91

Total direct cost $ 9,995,437.00

Fig 5-1. Direct capital costs in SAM

5.1. Generation

Following the steps described in section [3-3], a 3D map for all sites was designed. All relevant data is summarised below. In blue are the active surfaces, panels, and in red there are the buildings that throw shade on the panels. Panels were placed 0.01m above the surface under them to accounts for the structure holding them.

5.1.1. Leganés

Panels in the different buildings; Betancourt, Juan Benet, Torres Quevedo and the sports centre, were placed as shown in figure [5-2], figure [5-4], figure [5-3] and figure [5-5] respectively.

A total of 1.17MW was installed all over the campus.

- Betancourt building

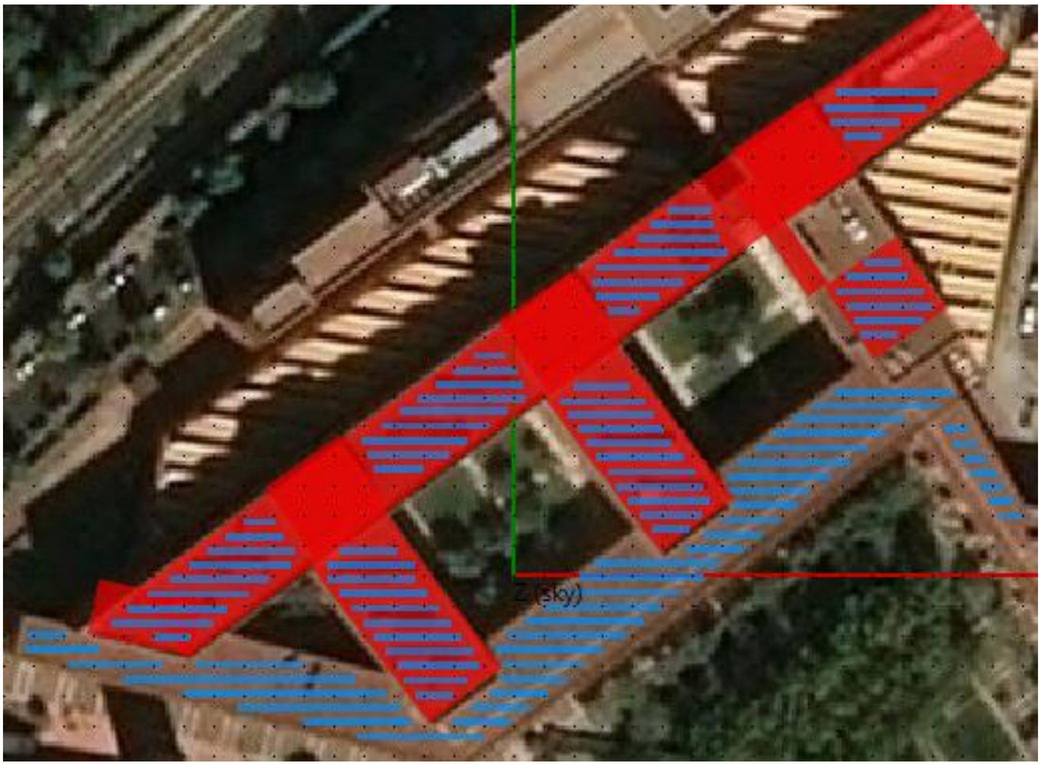


Fig 5-2. Panel arrangement in Betancourt building

TABLE 5-1. RESULTS FROM PV SYSTEM IN BETANCOURT BUILDING

DC Power (kW)	522.92
AC Power (kW)	450
DC/AC	1.16
Annual energy (year 1)	666,23 kWh
Capacity factor (year 1)	17.70%
Performance ratio (year 1)	0.75
Net capital cost	$780,463
Shading loss (%)	2.30%

Looking at figure [5-2], the spaces selected for the panels were chosen because they can be easily accessed by the team in charge of the installation. The three squares in between the panels were left empty of them as that space was chosen for the inverters.

- Torres Quevedo

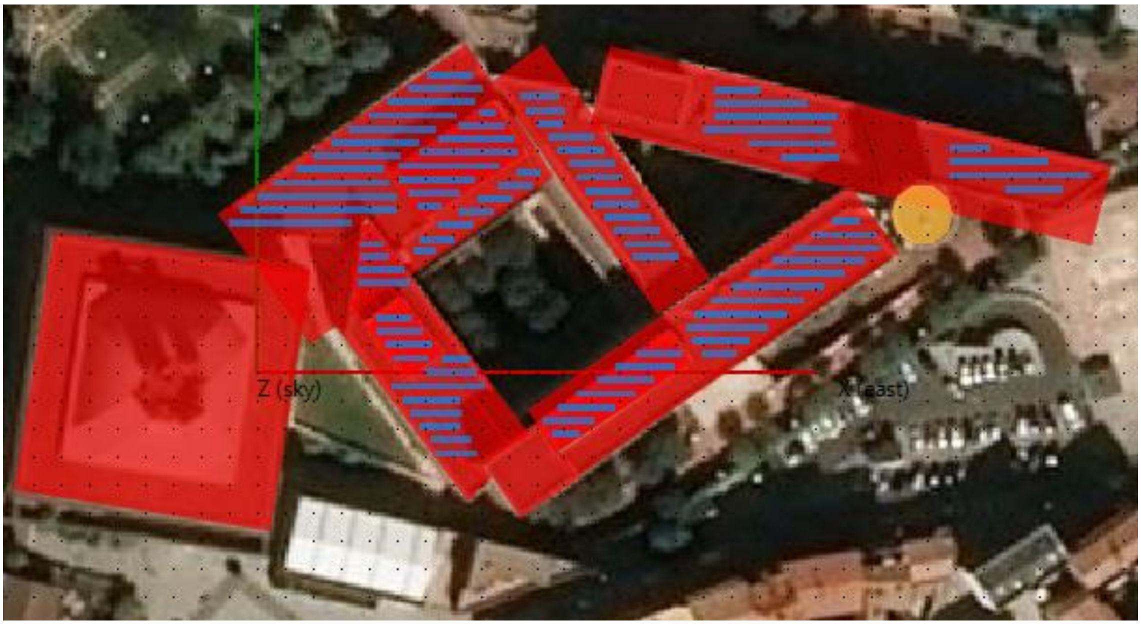


Fig 5-3. Panel arrangement in Torres Quevedo building

TABLE 5-2. RESULTS FROM PV SYSTEM IN TORRES QUEVEDO BUILDING

DC Power (kW)	285.595
AC Power (kW)	253.29
DC/AC	1.13
Annual energy (year 1)	450,669 kWh
Capacity factor (year 1)	18.00%
Performance ratio (year 1)	0.77
Net capital cost	$519,495
Shading losses	3.15%

In figure [5-3], the leftmost building is the campus's library and the yellow cylinder is a tower, which being higher than the panels placed in the building, its shading effect must be accounted for.

- Juan Benet

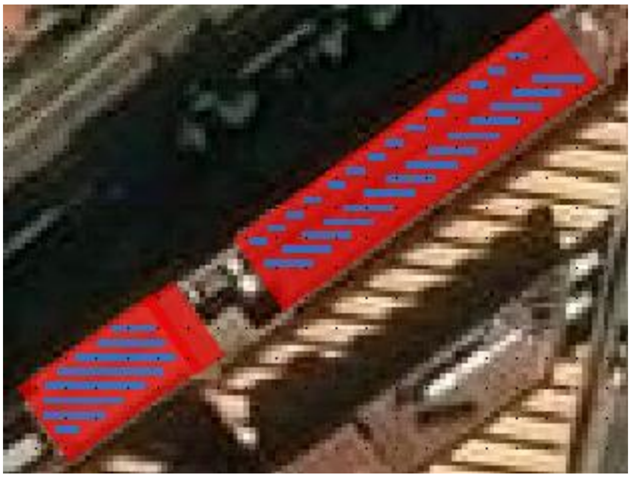


Fig 5-4. Panel arrangement in Juan Benet building

TABLE 5-3. RESULTS FROM PV SYSTEM IN JUAN BENET BUILDING

DC Power (kW)	88.494
AC Power (kW)	72
DC/AC	1.23
Annual energy (year 1)	121,447 kWh
Capacity factor (year 1)	15.70%
Performance ratio (year 1)	0.67
Net capital cost	$160,970
Shading loss (%)	2.83%

Inverters here would be placed to the left of the figure, of even in Betancourt building, as cables would only cross a small roof.

- Alfredo di Stephano Sports Centre

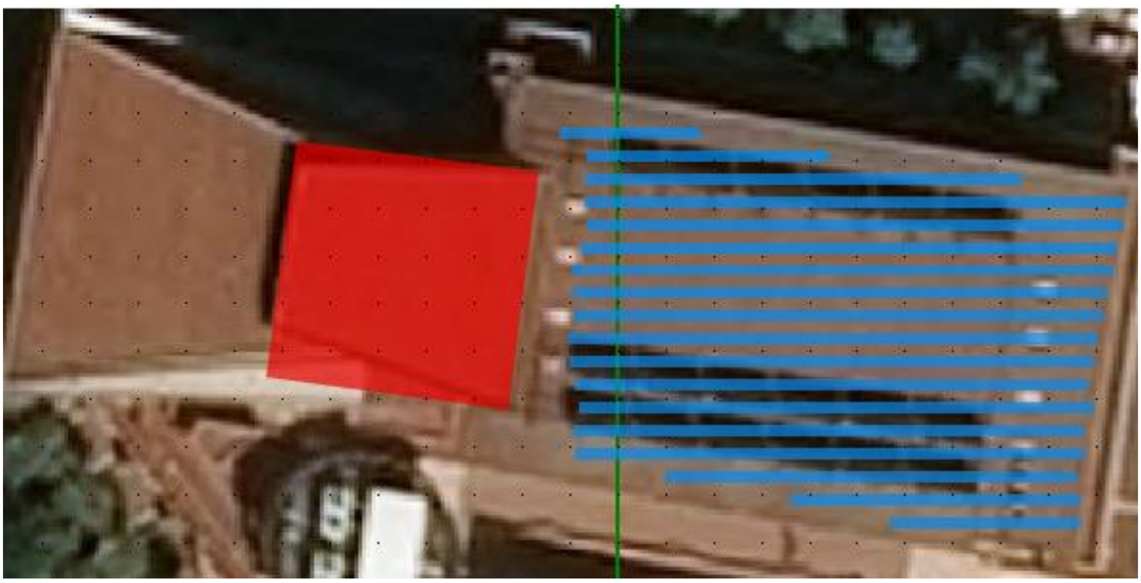


Fig 5-5. Panel arrangement in sports centre

TABLE 5-4. RESULTS FROM PV SYSTEM IN SPORTS CENTRE

DC Power (kW)	276.544
AC Power (kW)	220
DC/AC	1.26
Annual energy (year 1)	337,953 kWh
Capacity factor (year 1)	14.00%
Performance ratio (year 1)	0.59
Net capital cost	$745,502
Shading loss (%)	2.279

In figure [5-5], a red box has been used as an approximation for the shading caused by auditorium. The side of this building facing the PV system is inclined, but as SAM's 3D tool has limited shapes, this geometry has been used. Some extra space has been set between the panels and the auditorium's wall to reduce shading losses.

5.1.2. Colmenarejo

The three different buildings and the two plots in Colmenarejo’s campus are shown below. For the plots, not all land was used to allow for the installation of the needed inverters.

A total of 9.82MW were installed.

- Library

Fig 5-6. Panel arrangement in Colmenarejo’s library

TABLE 5-5. RESULTS FROM PV SYSTEM IN COLMENAREJO’S LIBRARY

DC Power (kW)	78.438
AC Power (kW)	60.14
DC/AC	1.3
Annual energy (year 1)	118,203 kWh
Capacity factor (year 1)	17.20%
Performance ratio (year 1)	0.77
Net capital cost	$211,452
Shading loss (%)	3.826

The only building throwing shade on the panels is the yellow cylinder. To its left, a part of the rooftop has been left empty as any panel here would be shaded by the cylinder. This place would be used for the inverter/s.

- Cafeteria

Fig 5-7. Panel arrangement in Colmenarejo's cafeteria

TABLE 5-6. RESULTS FROM PV SYSTEM IN COLMENAREJO'S CAFETERIA

DC Power (kW)	48.575
Paco (kW)	42
DC/AC	1.15
Annual energy (year 1)	72,977 kWh
Capacity factor (year 1)	17.30%
Performance ratio (year 1)	0.78
Net capital cost	$130,124
Shading Loss	3.69%

No objects near would shade the panels, hence no red objects have been placed in the simulation. Right on top of the building, an extra space is found for the inverters.

- Student residence

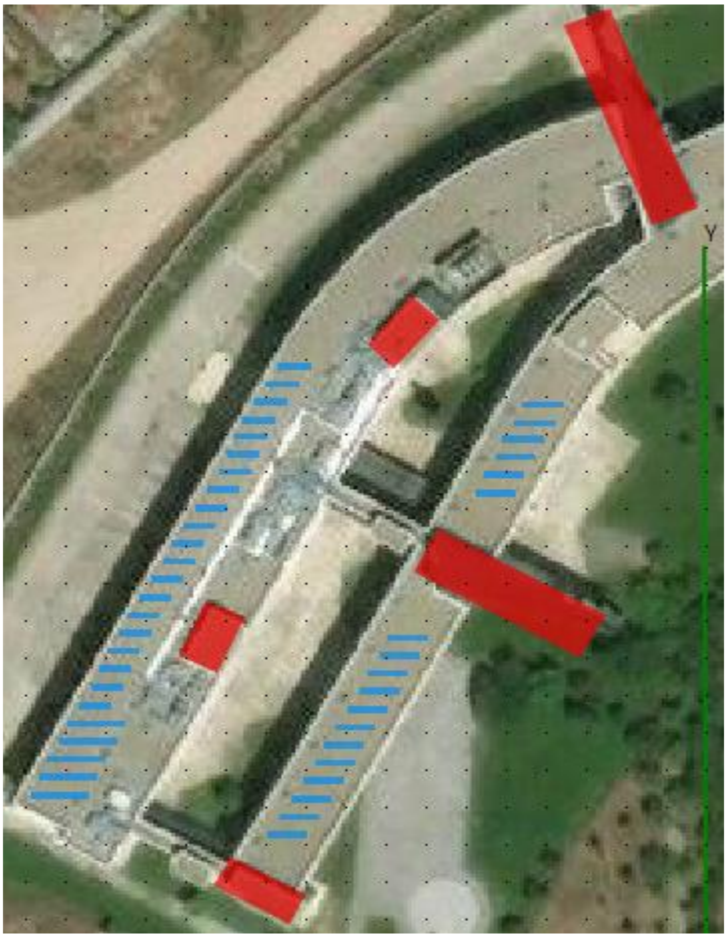


Fig 5-8. Panel arrangement in Colmenarejo's student houses

TABLE 5-7. RESULTS FROM PV SYSTEM IN COLMENAREJO'S STUDENT RESIDENCE

DC Power (kW)	67.041
Paco (kW)	60.04
DC/AC	1.12
Annual energy (year 1)	100,986 kWh
Capacity factor (year 1)	17.20%
Performance ratio (year 1)	0.79
Net capital cost	$180,728
Shading loss (%)	3.7

- Plots in campus’s premises

Fig 5-9. Panel arrangement in Colmenarejo campus’s plot

TABLE 5-8. RESULTS FROM PV SYSTEM IN COLMENAREJO CAMPUS’S PLOT

DC Power (kW)	442.471
Paco (kW)	375
DC/AC	1.18
Annual energy (year 1)	627,876 kWh
Capacity factor (year 1)	16.20%
Performance ratio (year 1)	0.73
Net capital cost	$1,192,803
Shading Loss	2.77%

As in other locations, buildings have been approximated to a cube or cuboid in order to consider its shading on panels, which may only happen in the early and late hours of the day. If the display seen in figure [5-9] is compared to the areas depicted in figure [3-2], it can be observed that not all area in the plot has been used. Again this has been reserved for inverters, as the plot is limited by a fence and placing the inverter on buildings far away not a favourable option due to cable layout and higher losses.

- Plot outside campus

Fig 5-10. Panel distribution in extra plot in Colmenarejo

TABLE 5-9. RESULTS FROM PV SYSTEM IN EXTRA PLOT IN COLMENAREJO

DC Power (kW)	5492
Paco (kW)	4400
DC/AC	1.25
Annual energy (year 1)	7,284,202 kWh
Capacity factor (year 1)	15.10%
Performance ratio (year 1)	0.68
Direct capital cost	$9,989,921
Shading Loss	4.64%

The potential of the extra plot in Colmenarejo can be seen in figure [5-10]. With the objective of maximizing installed capacity, a total of 5.5MW of DC power was set up. If this case was to be carried along, the trees at the site and around it would need to be cut, to reduce shading losses.

- Campus park

This simulation was performed through the SAM's self-shading tool, instead of the 3D, as the green area (see figure [map of Colmenarejo]) could be approximated to a rectangle of area 23000m^2. With the same spacing and tilt angle as the other systems, the results of analysis gave:

TABLE 5-10. RESULTS FROM PV SYSTEM IN COLMENAREJO CAMPUS PARK

DC Power (kW)	3298.42
AC Power (kW)	2601.8
DC/AC	1.27
Annual energy (year 1)	4,260,626 kWh
Capacity factor (year 1)	14.70%
Performance ratio (year 1)	0.66
Net capital cost	$5,999,806
Shading loss (%)	3.81

5.2. Scenarios

Seven different combinations of load and generation will be considered in this project. In addition, two of those will be further studied with the use of batteries, giving a total of nine scenarios. The objective of using different cases is to analyse renewable penetration and investment on cases with and without excess, and open for remuneration.

The final aim of this study is to conclude if full self-consumption is an option for both campuses.

In this section they are explained, allocated to a type of self-consumption and direct capital costs for each installation is given.

5.2.1. Scenario 1

In this scenario, a 100kW PV installation has been installed in Colmenarejo. With this chosen capacity and an annual demand of 858.5 MWh, it would be a case of self-consumption with excess and open for remuneration. This would mean that the university would get money for the energy injected into the grid, which amounts for 11.4MWh on the first year.

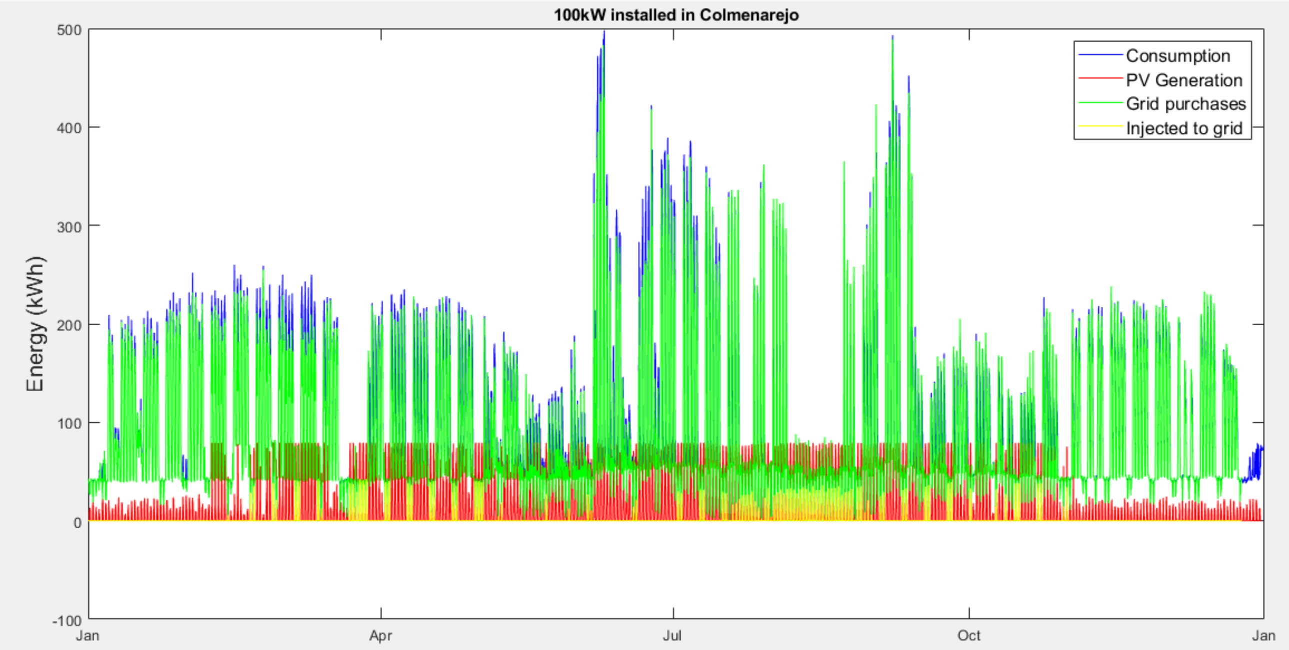


Fig 5-11. Power flow in scenario 1

In august, when demand is at its lowest and generation at an above average value, energy is injected into the grid at mid-day. Of course at night demand is satisfied through purchases from the grid.

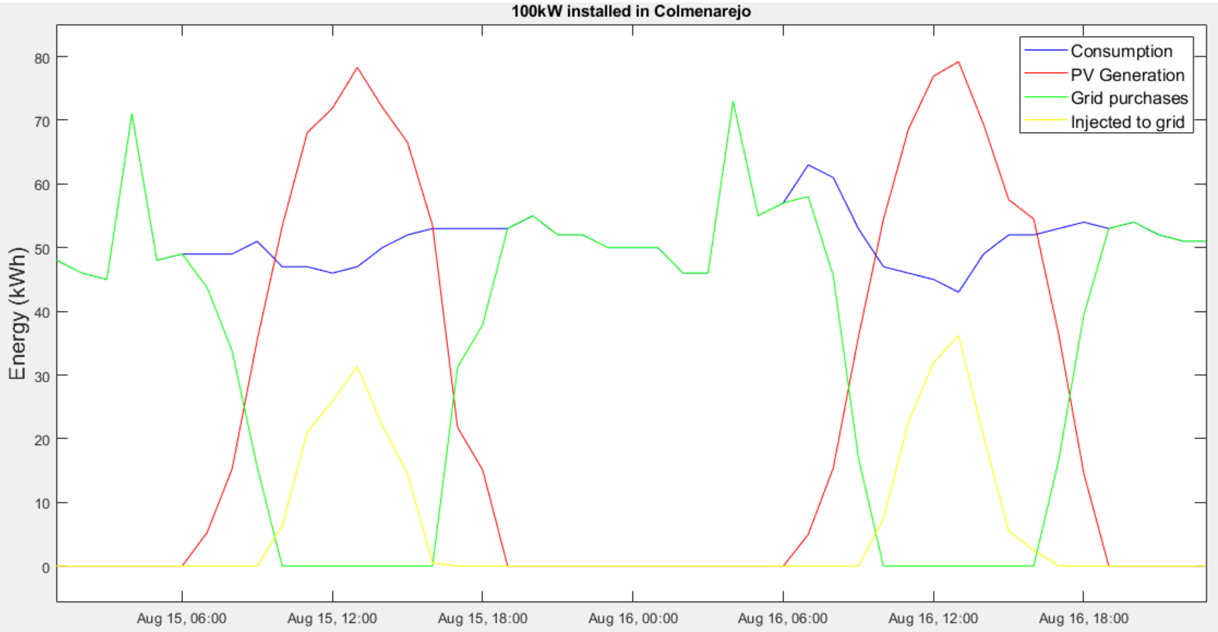


Fig 5-12. Power flow in mid-August for scenario 1

Weekend patterns are shown in figure [5-13], as demand drops for two days only (Saturday and Sunday) and generation surpasses demand, but throughout the week demand is too large for it to be covered with the system. The effect of clouds can be seen too, as on April 14th the generated power shows decrease and spikes, whereas on the 15th the curve is smooth.

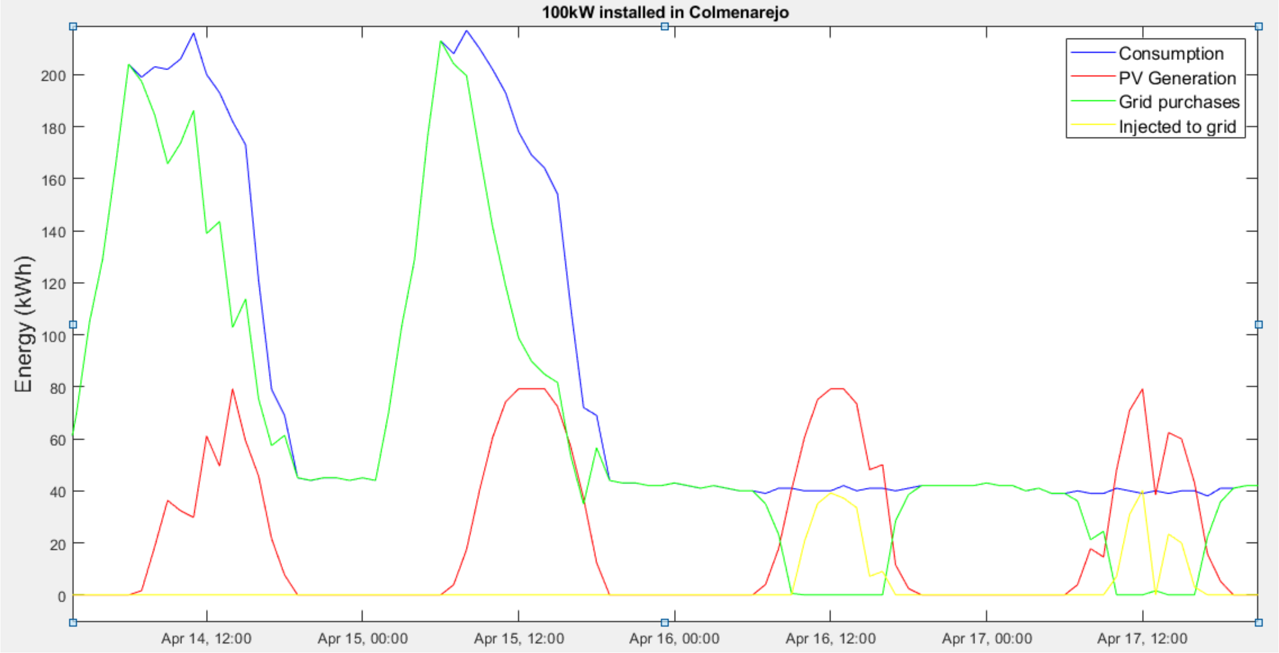


Fig 5-13. Power flow in mid-April for scenario 1

5.2.2. Scenario 2

This scenario has the same objective as the previous one, check if remuneration of injected energy is possible. However, in this case demand is too big (9.69GWh) and is never fully covered by generation. Therefore all energy generated by the installation is consumed and no remuneration is possible. This system will require of an anti-spillage system, as mentioned in section [1.1.2.2].

Looking into figure [5-14], generation is way below load, hence most of the energy demand must be bought from the grid.

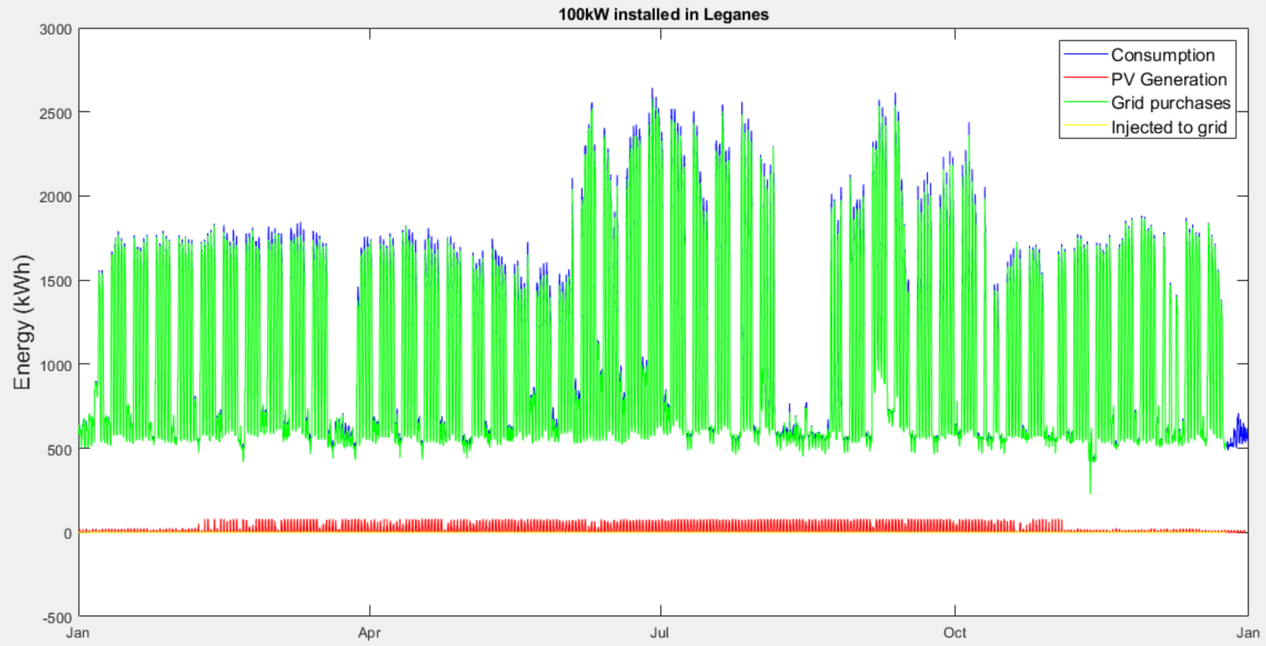


Fig 5-14. Power flow in scenario 2

Viewing closer into the graph, the effect of the energy generated from the PV can be observed, varying from a sunny day and a cloudy day. The comparison can be drawn between May 15th and May 16th, were two different generation profiles cause a bigger and smaller difference between demand and grid purchases. However, regardless of the day a very small percentage of the load is covered.

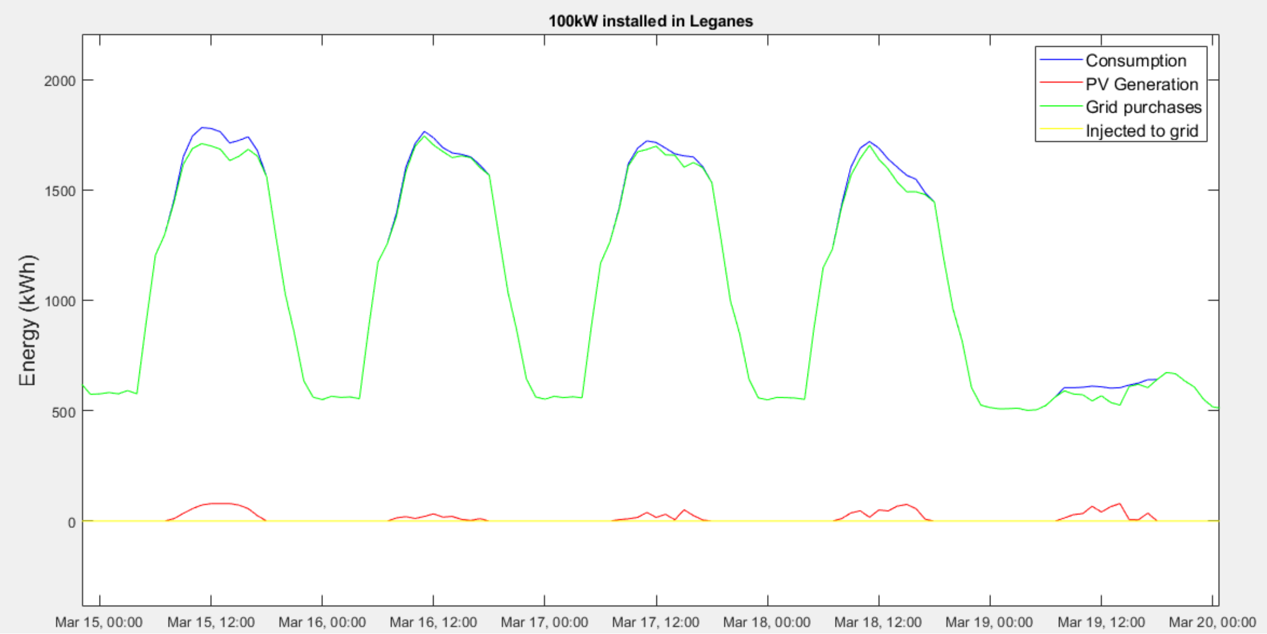


Fig 5-15. Five day period for the power flow in scenario 2

5.2.3. Scenario 3

Here, a hypothetical situation has been chosen. By using up all available land and rooftops in Colmenarejo's campus, a total of 9.82 MW would be installed, resulting in a generation of 13GWh for the first year. This would give a case of self-consumption with excess and no remuneration possible. It must be mentioned that this case would never be realistically considered as it would mean an unnecessary investment for such a small load, resulting in a huge amount of energy injected into the grid (12.4GWh) that would give no benefit.

The previous statement can be seen in the figure below, were injection to the grid nearly matches generation from the system.

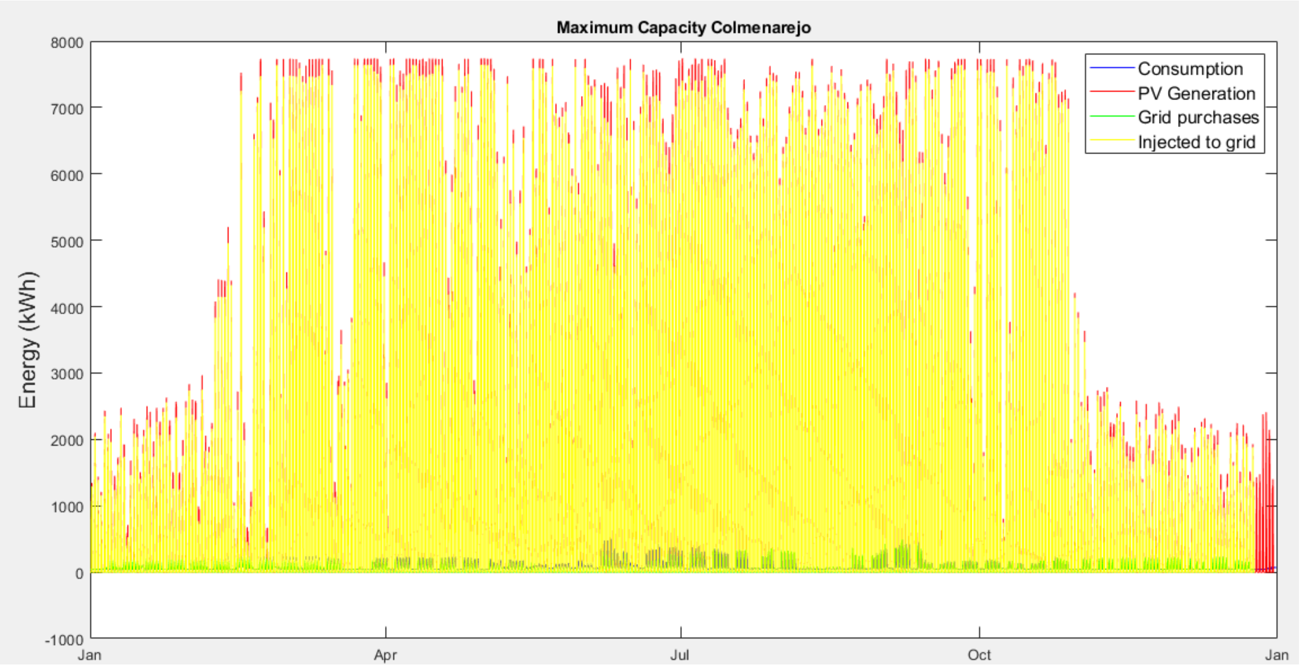


Fig 5-16. Power flow in scenario 3

Even in winter, where solar irradiance is at a minimum, generation tops demand at peak hours.

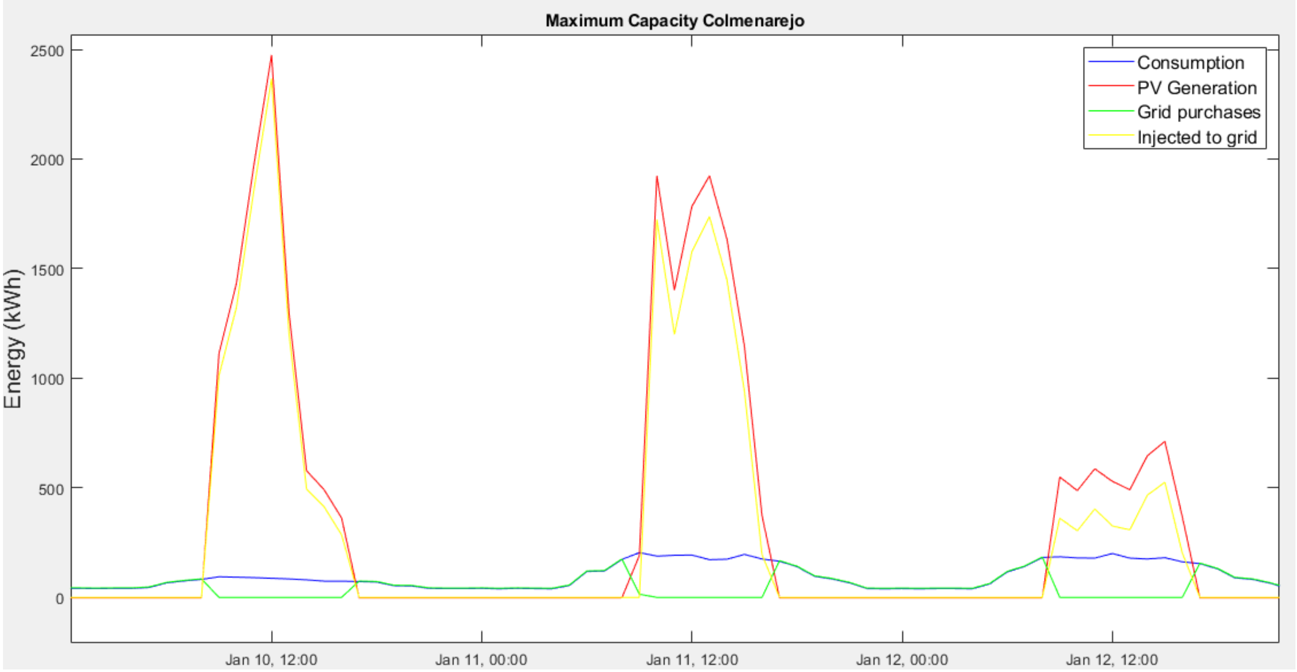


Fig 5-17. Power flow in January for scenario 3

5.2.4. Scenario 4

In this scenario, a more realistic case can be found. A total of 1.17MW can be installed in Leganés and an excess situation would be seen, but again no remuneration. Biggest excess can be found in the holiday's period were load decreases notably.

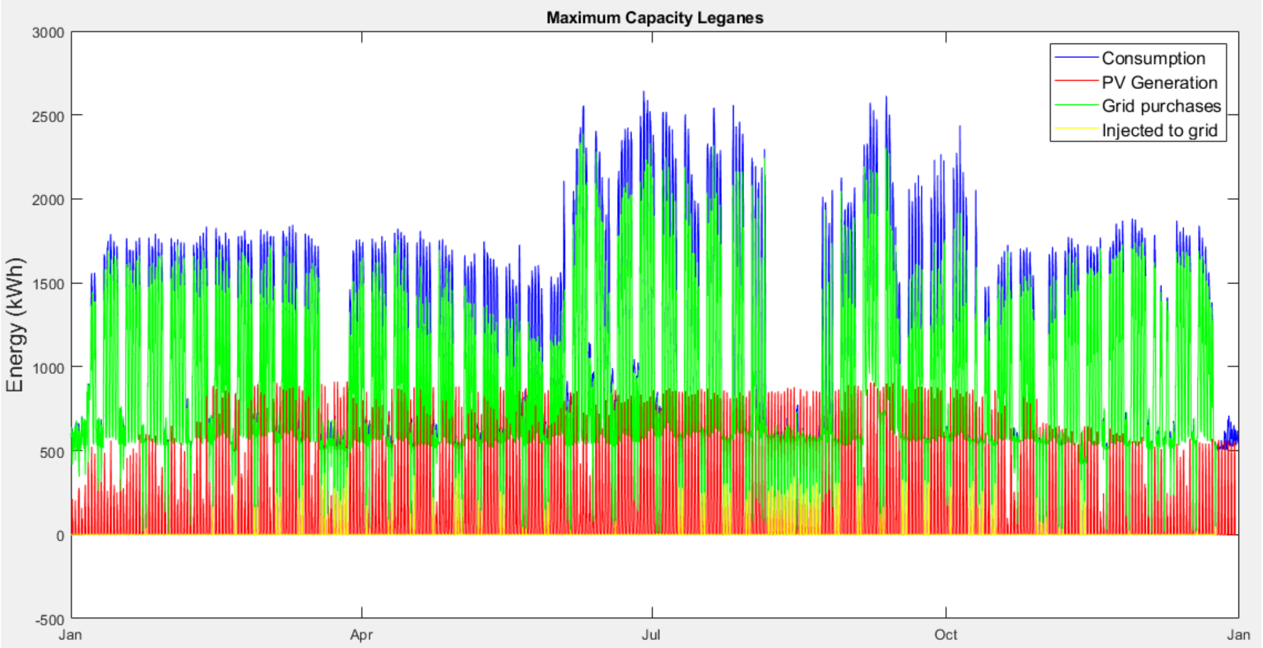


Fig 5-18. Power flow in scenario 4

This case is now further studied applying batteries, as it allows for a higher renewable penetration and setting energy injection to the grid to zero. The effect of batteries is compared below.

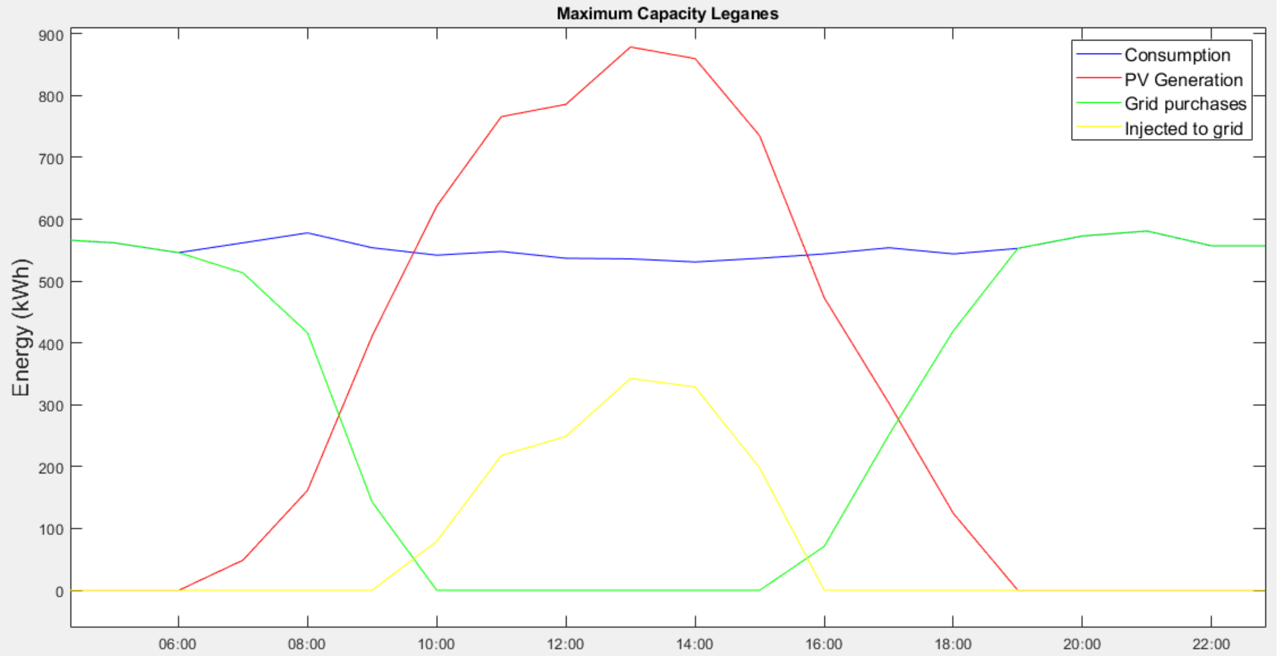


Fig 5-19. Power flow for a one day period in august

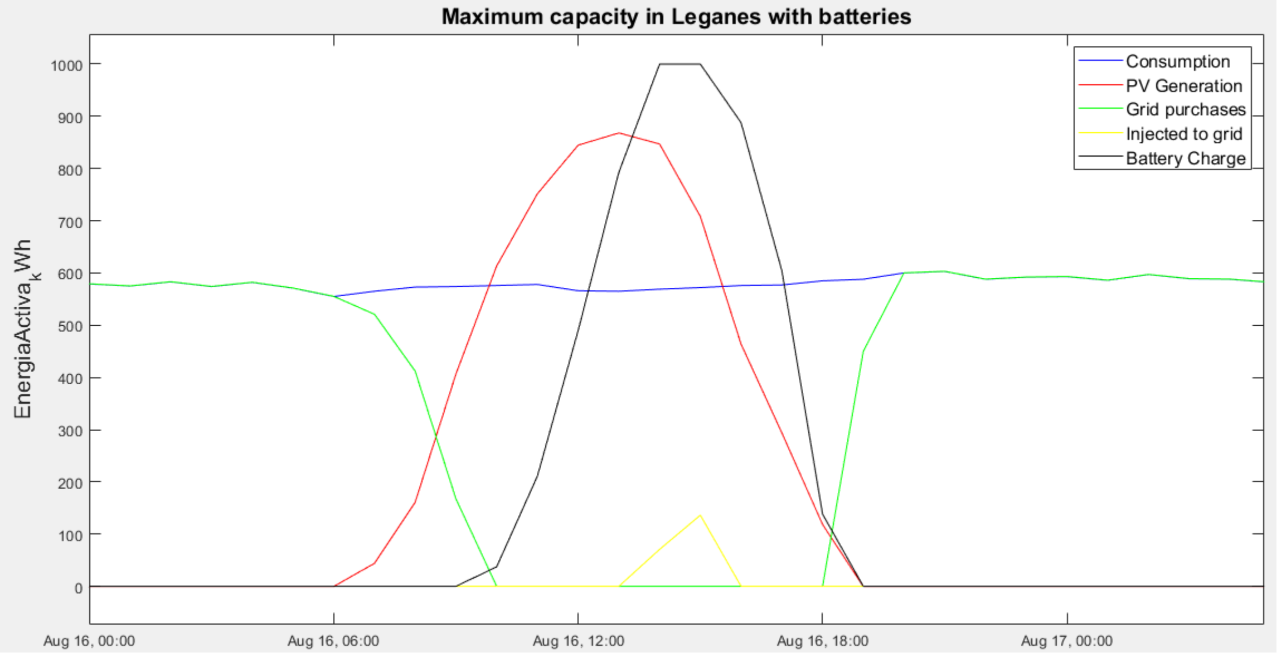


Fig 5-20. Power flow for a one day period with batteries

In figure [5-19] excess of energy is being injected to the grid. In figure [5-20], that excess energy is being stored into the batteries up to their limit (1 MW), reached at 13:00, where energy is again injected into the grid. If enough battery capacity is chosen, grid injections can be reduced to zero. The effect of battery capacity on grid injections can be seen in figure [5-21].

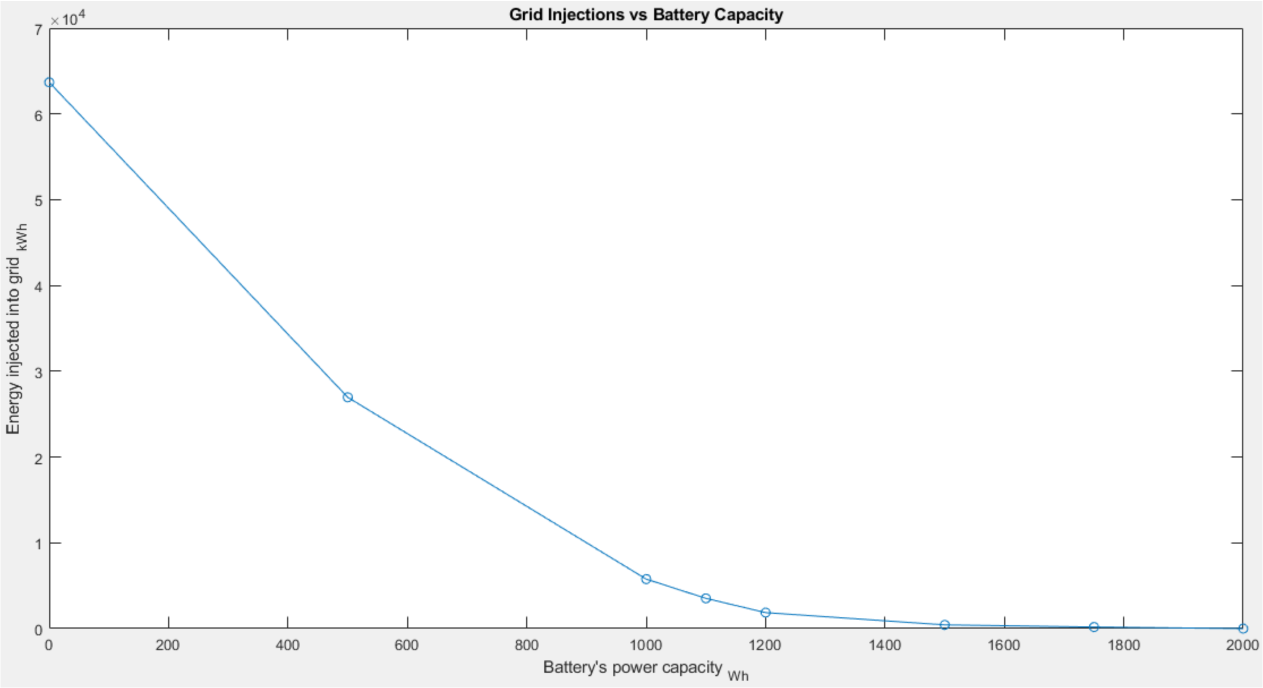


Fig 5-21. Effect of batteries on grid injections in scenario 4

From an energy point of view, a 500kWh battery bank could be installed to increase penetration of the PV system and save 36.7MWh generated. Such battery would have dimensions of 600x245x280cm [29], a size that could be installed in the university's premises.

It must be mentioned that if full self-consumption, defined in the abstract, was set as objective, Leganés would require a total of 6.17MW installed. Using up all the space available, a total of 1.57GWh on the first year would be generated, leaving a total of 7.12GWh of demand, requiring of an extra 5MW of installed capacity.

5.2.5. Scenario 5

This option will allow the installation of the PV system to happen without altering life at the campus. In addition, approximately 5.5MW could be installed. This would mean an excessive energy generated, as seen in scenario 3.

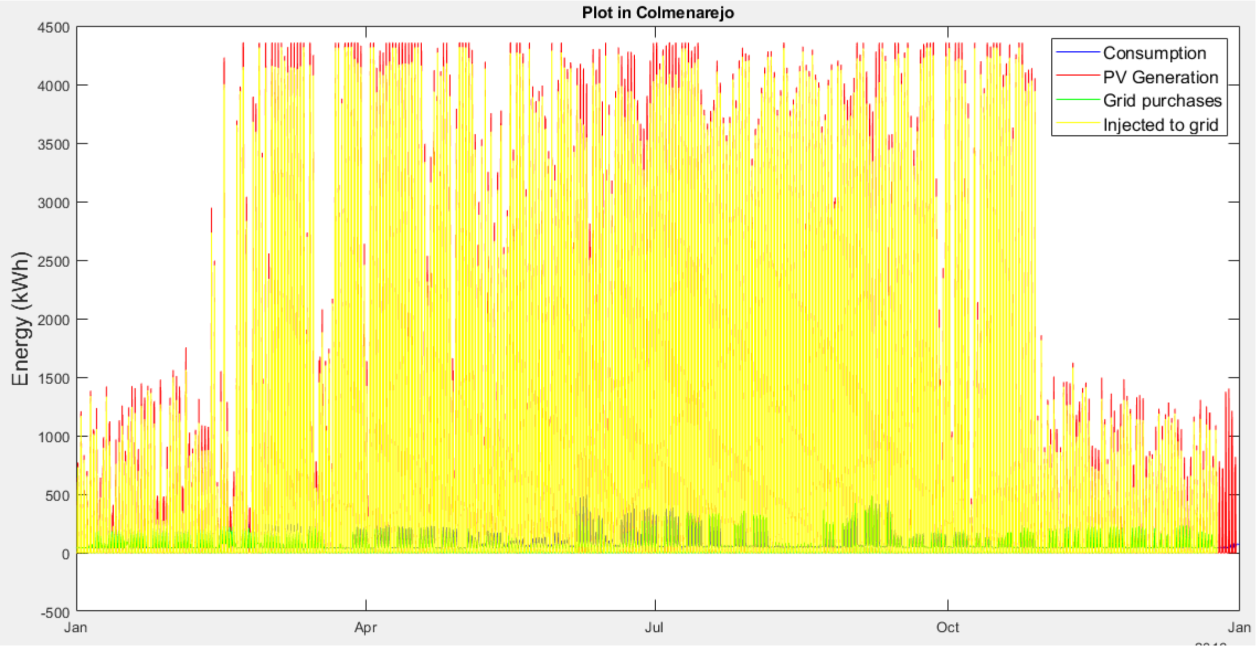


Fig 5-22. Power flow in scenario 5

If the objective would be full self-consumption, with Colmenarejo's yearly demand (858.5 MWh), a system of approximately 600kW would be needed. With the available land there, the entire generation unit could fit. All excess energy would be injected into the grid with no remuneration.

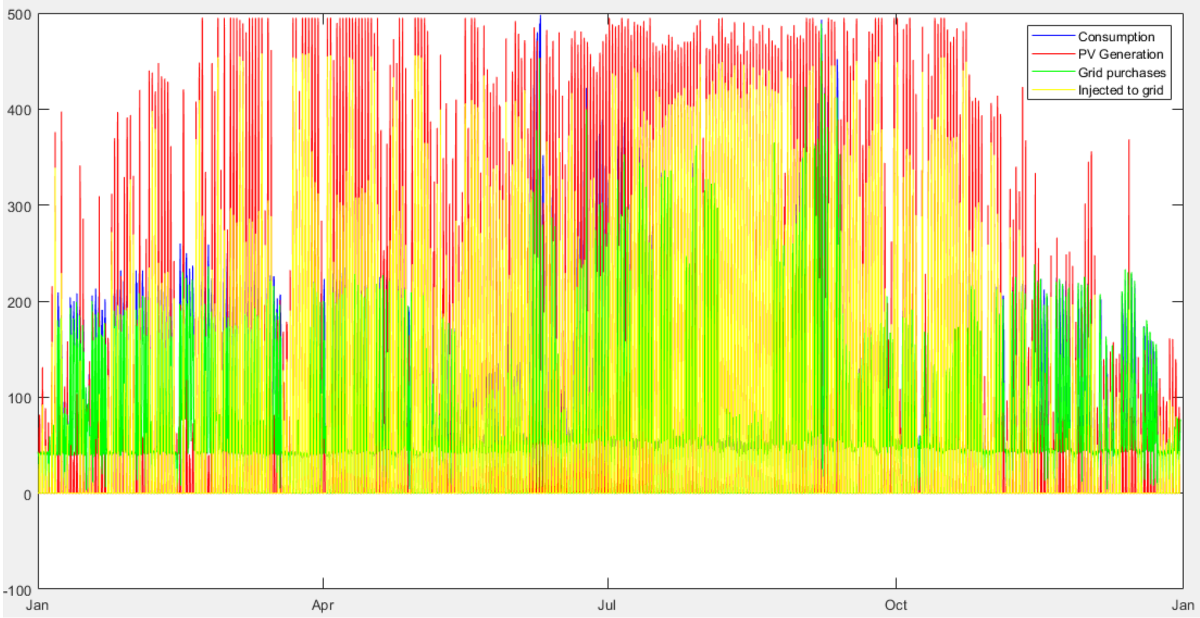


Fig 5-23. Power flow full self-consumption Colmenarejo

5.2.6. Scenario 6

The main issue in this case is that Leganes and Colmenarejo are far away, and self-consumption is for now seen for systems within the grid that is consuming it, or associated to it. However, regulation in Spain is changing constantly and such case may become a reality one day. A non-remuneration case is seen here. The generating unit is oversized as through most of the year, most of the energy is injected into the grid.

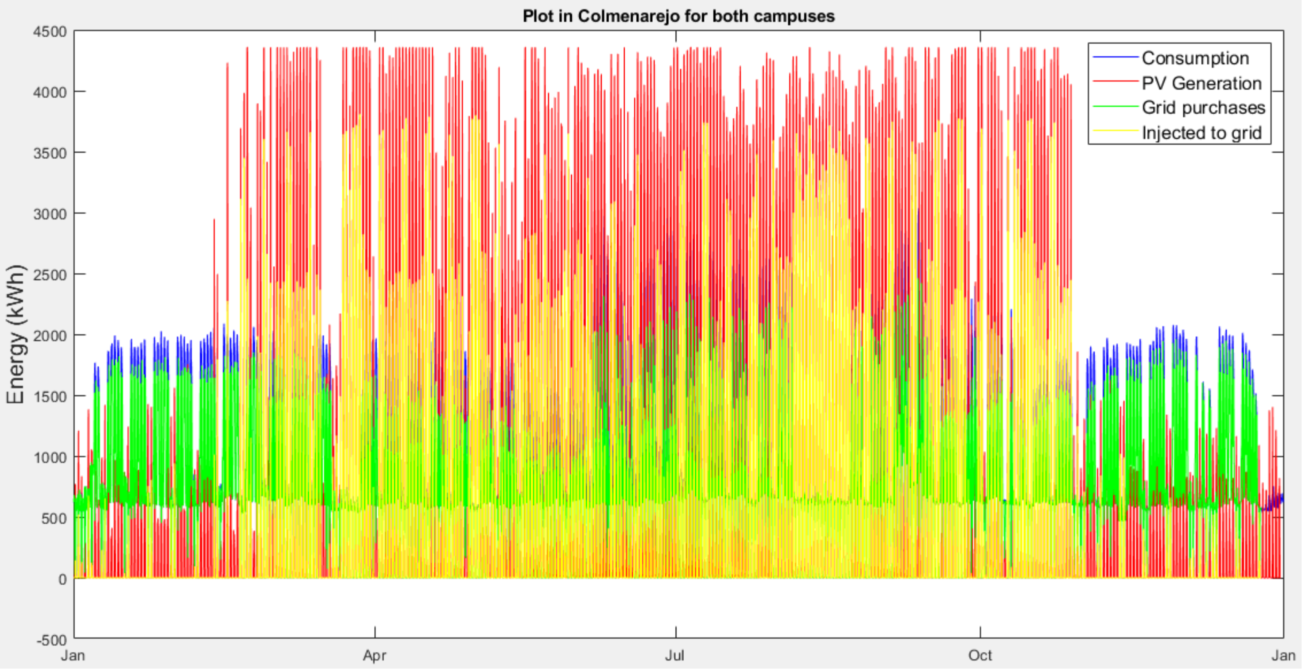


Fig 5-24. Power flow in scenario 6

While a large amount of purchases from the grid are seen (around 5.5GWh/year) especially through the first and last couple of months of the year, excess injection into the grid appears through most of the year. In figure [5-25], energy generated exceeds consumed through most of the day. A quick drop can be seen, probably due to clouds, at around 14:00, where grid purchases rise quickly and injections drop.

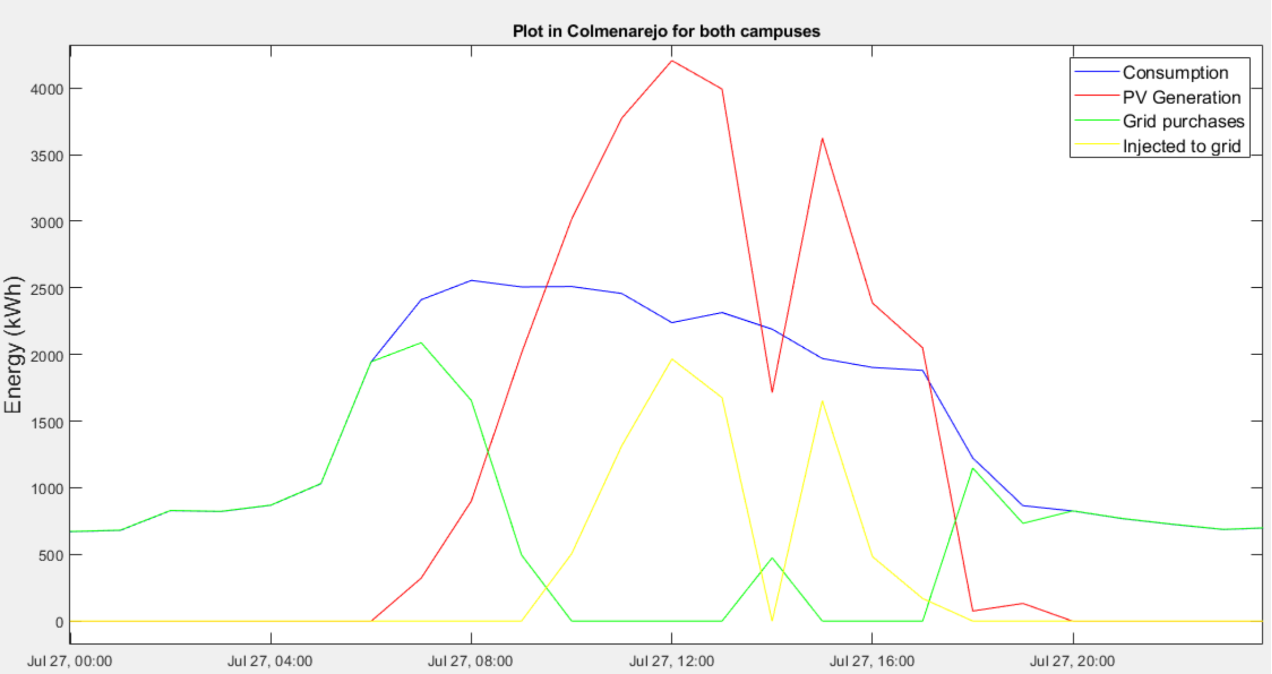


Fig 5-25.Power flow on the 27th of July for scenario 6

To match generation with the total consumption of both campuses, a system of 6.77MW would be needed. This would yield an even bigger amount of grid injections and would need of installation on both campuses.

5.2.7. Scenario 7

This case would be similar to the previous one. Approximately 11MW would be installed in this scenario. It would be defined as a self-consumption with excess and no remuneration. As in the previous case, the PV system is oversized; a large amount of energy is being injected into the grid and therefore lost.

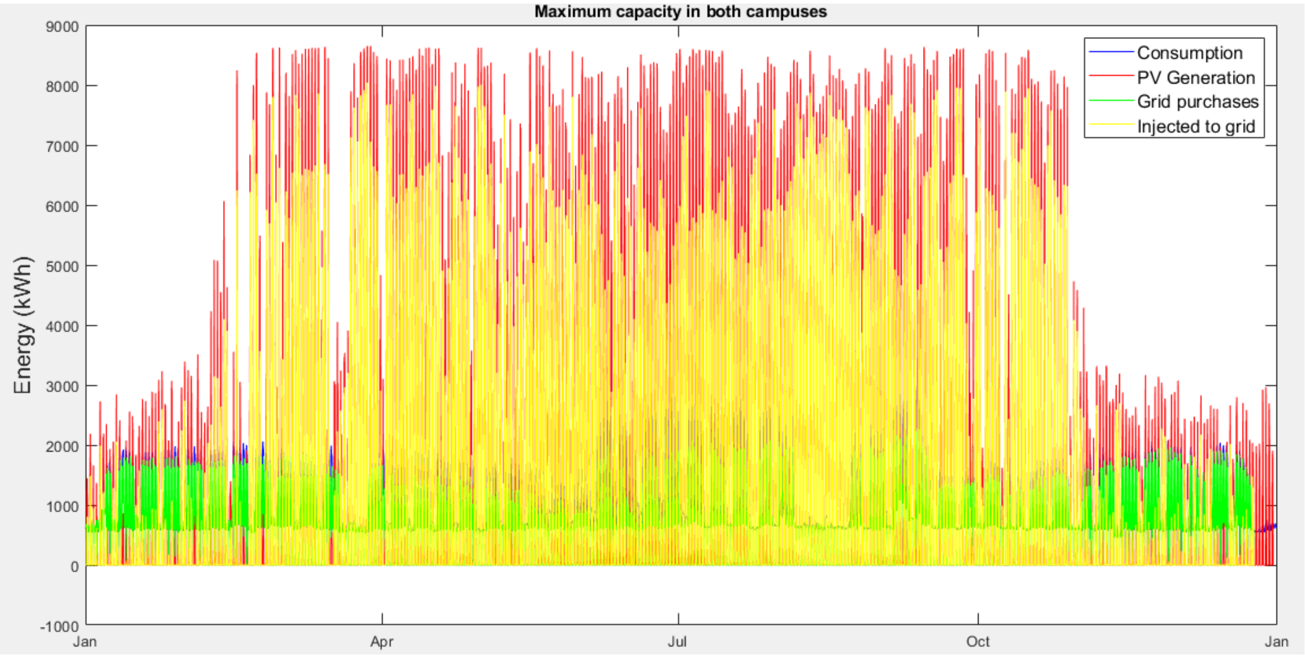


Fig 5-26. Power flow in scenario 7

Analysing the effect of batteries, with the objective of further reducing grid dependence or even achieving full renewable penetration. When interacting with batteries in scenario 4, capacity is sized looking at the excess of energy as such value is low enough for zero energy injection to be achieved under a reasonable battery size. On the contrary, in this case batteries are to be sized focusing on grid purchases. Eliminating grid injections in this scenario would not be realistic.

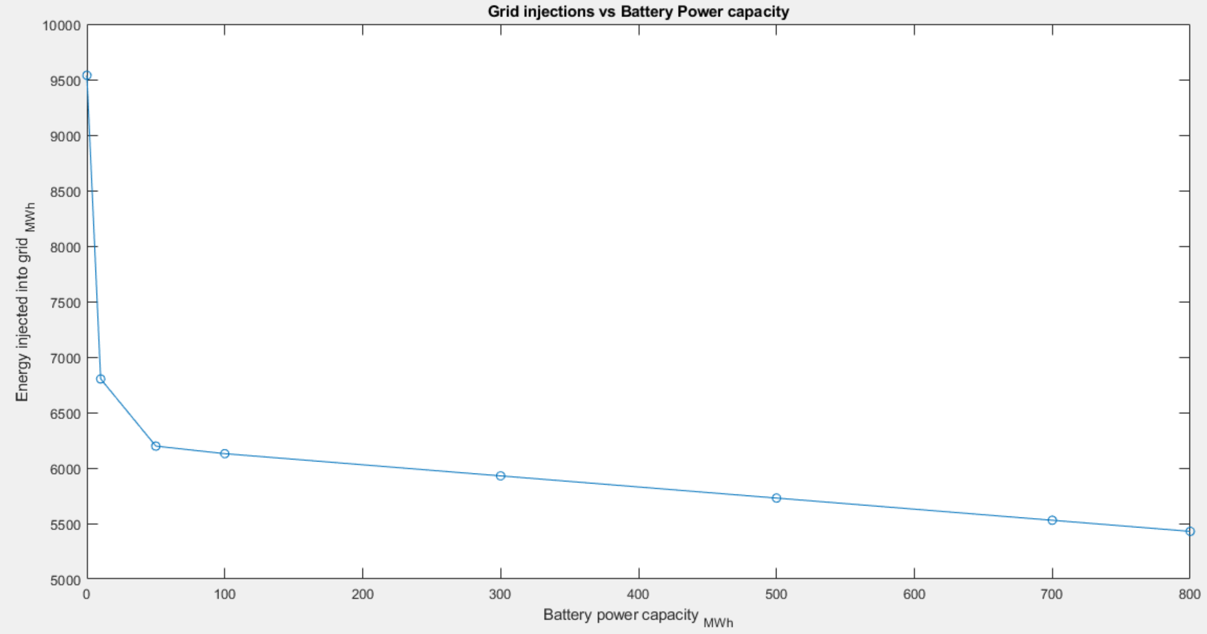


Fig 5-27. Effect of batteries on grid injections in scenario 7

A summary of the main scenarios can be seen below.

TABLE 5-11. SUMMARY OF SCENARIOS STUDIED

Scenario	**Consumption (MWh/yr)**	**Installed Capacity (kW)**	**Energy Generated (MWh/yr)**	**Grid injections (MWh/yr)**	**Self-consumption scheme**	**Direct Capital Cost (*1000€)**
1)	858,5	100	134.5	1.142	Excess and remuneration	16.504
2)	8694,5	100	136.5	0	No excess	16.504
3)	858,5	9821	12999	12380	Excess, no remuneration	11705.03
4)	8694,5	1173,6	1576.3	63.7	Excess, no remuneration	2206.43
5)	858,5	5492	7284.2	6792.2	Excess, no remuneration	9995.44
6)	9553,0	5492	7284.2	3280.6	Excess, no remuneration	9995.44
7)	9553,0	10995	14575	9538.3	Excess, no remuneration	13911.46

5.3. Statistical analysis

From the results of equal annual demand and consumption for full self-consumption in Colmenarejo, the following box plot can be drawn:

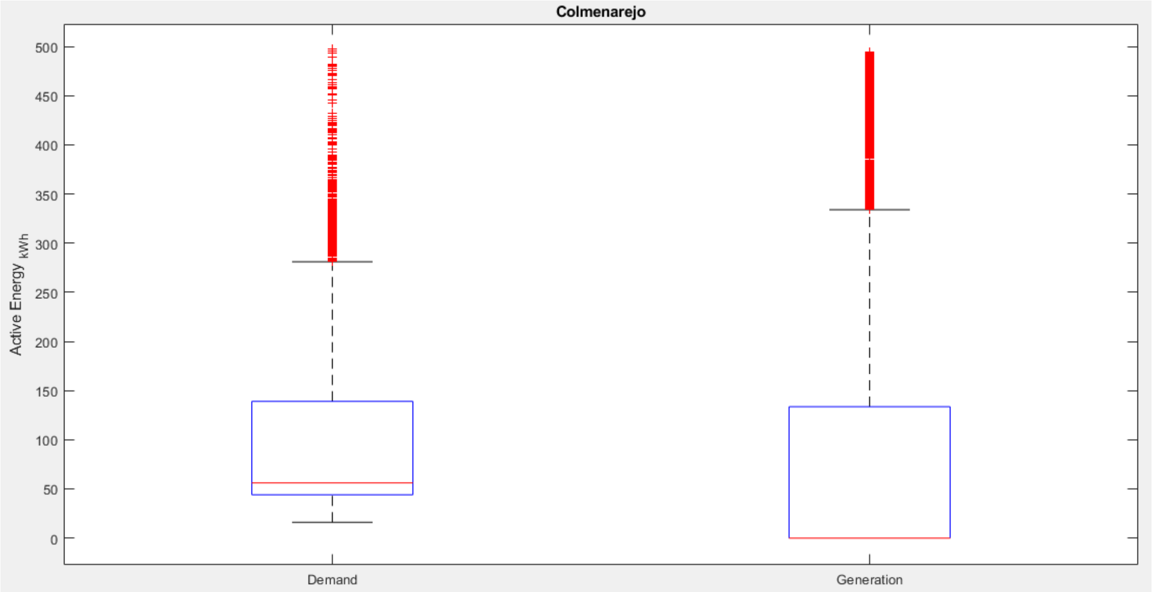


Fig 5-28. Box plot full self-consumption for Colmenarejo

Looking first into generation, the median is shown as 0. Taking into account that PV systems generate only in the hours when sunlight hits the panels, more than half of the hours the system will have no energy generated, explaining the median value.

Furthermore, in the moments when the panels are generating, energy rises quickly to reach its daily maximum at around mid-day. In summer, when more sunlight strikes the panels, maximum values are seen. As these maximum results are being compared with 0 (no generation), they are seen as extreme.

The distribution of median and box bottom values shown for demand in Colmenarejo's campus suggests that load values for night-time and/or holidays are around 47kWh. This value is probably the consumption of basic elements that are not switched off during night, such as emergency lights, measurement devices… From the red crosses, maximum values, are consumption on peak days, when more students attend the university (e.g. exams), which are reflected as outliers in our plot because of its comparison with night time consumption. In addition, outliers may be due to errors in the data samples found in Colmenarejo.

With a combination of both campuses, boxplots for total self-consumption are shown below.

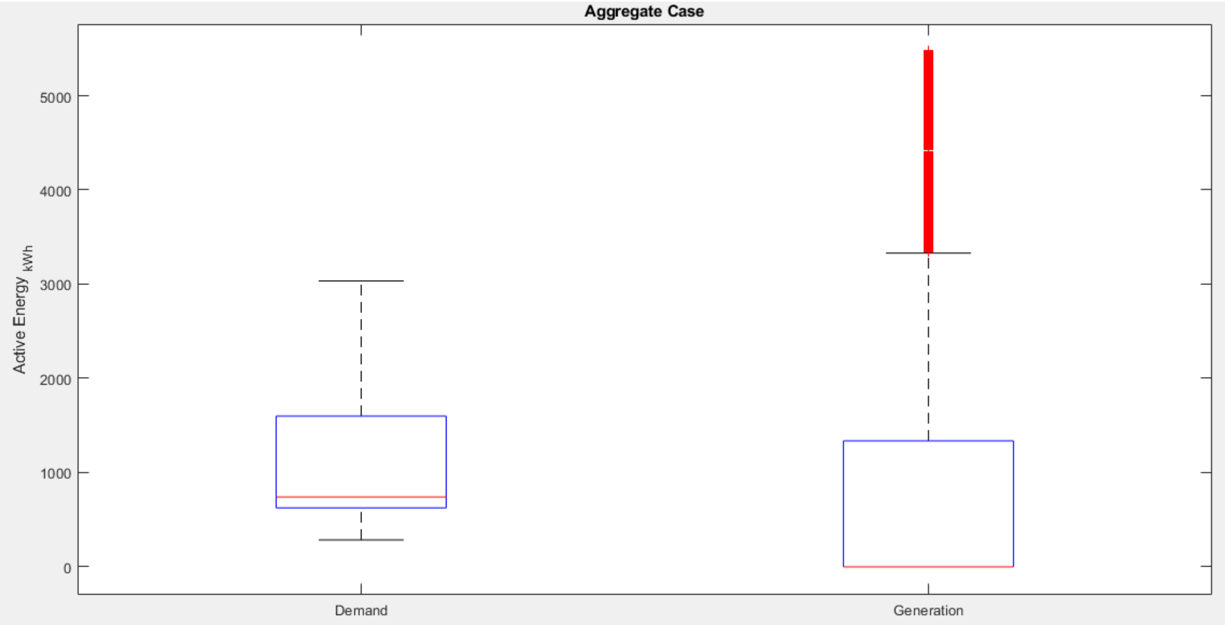


Fig 5-29. Box plot full self-consumption both campuses

Demand data shows that a quarter of the data lie between 625kWh and 737.5kWh. In addition, no outliers are to be found, despite Colmenarejo's demand having them. These two details are explained by the aggregate demand being 11 times bigger than only Colmenarejo's. A big share of the demand is roughly between the 600kWh and 750kWh, small difference. Once over the 50th percentile, data is more dispersed.

Generation in this case has again the maximum values bigger than the 75th percentile. This difference is larger than in the previous case as the PV system is bigger, hence if we compared both systems for similar weather data, both would have values of 0 for more than 50% of the time, but once they started producing the difference between one another would increase.

Percentile analysis for the two generation systems is seen in figure [5-30]. These show how at least half of the year the system is not generating and that once they start generating, over the 50th percentile, the bigger system shows bigger difference in percentiles.

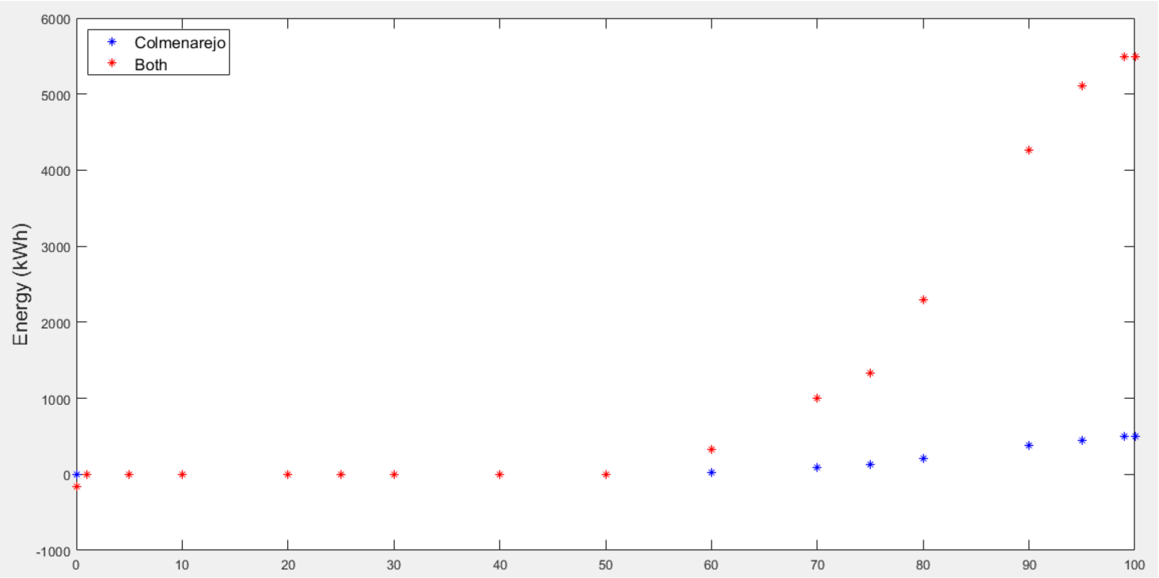


Fig 5-30. Percentiles for generation hour data

The effect of tilt was already explained in section [3.3.3]. In figure [6-4] it can be observed how for different tilt, generation is higher in certain periods. For tilts closer to 35º, chosen for our system, generation is higher through April to August. For 40º, 50º, 60º and 70º, the values analysed for winter, through January to March and October to December, generation is higher. It must be noted that increasing the tilt angle will mean more shading losses to back rows.

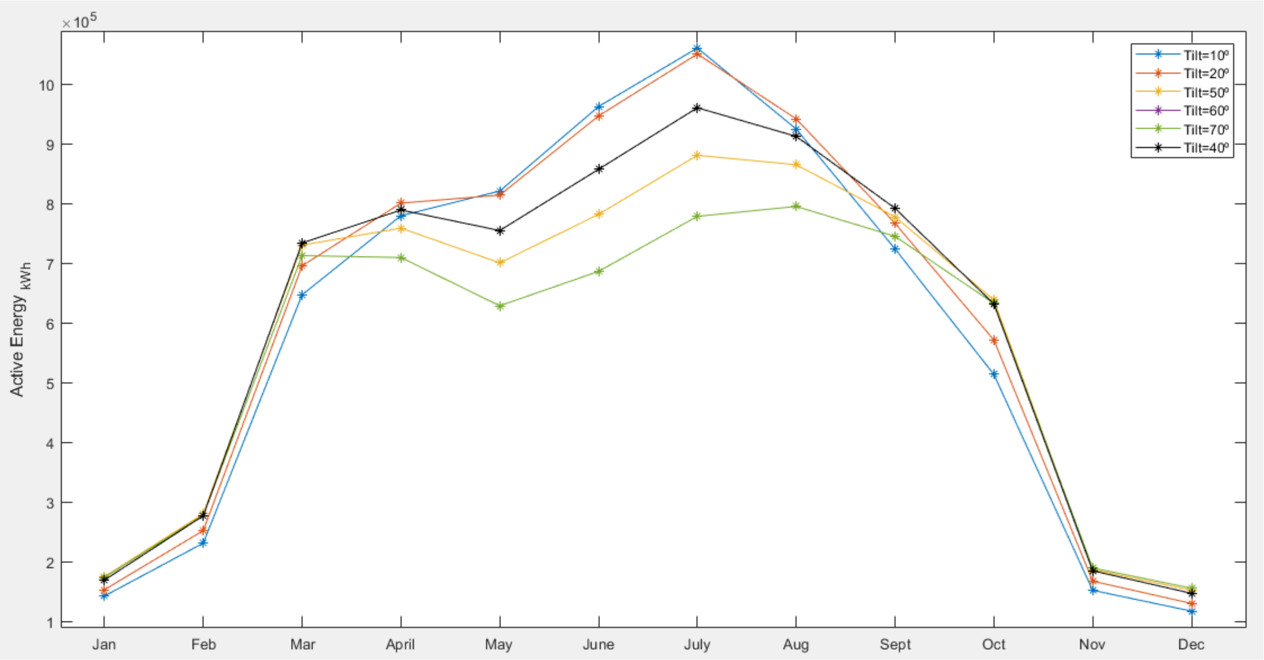


Fig 5-31. Monthly generation for different tilts

TABLE 5-12. ENERGY GENERATED FOR 20º AND 40º TILT

	Energy generated (MWh)		
	40º	**20º**	**Optimal**
January	**168,9**	152,7	168,9
February	**276,6**	251,8	276,6
March	**733,6**	695,2	733,6
April	788,7	**800,2**	800,2
May	754,3	**813,6**	813,6
June	856,9	**946,3**	946,3
July	960,0	**1046,3**	1046,3
August	912.0	**941,4**	941,4
September	**791,6**	766,3	791,6
October	**631,4**	571,0	631,4
November	**184,4**	167,1	184,4
December	**146,6**	129,7	146,6
Total	7204,8	7281,8	7480,8

For the chosen tilt of 35º, an analysis to check on the results obtained for distance between rows of panels in the system design phase was performed. SAM's macro "Subarray Layout Optimisation" with the fixed area of the extra plot in Colmenarejo. The results retrieved are shown on table [5-13]. It can be observed that the best case scenario for energy generation is the one with 1.24m of spacing.

TABLE 5-13. EFFECT OF ROW SPACING ON ANNUAL ENERGY

Spacing (m)	**Annual Energy (GWh)**	**Size (MW)**
4.96	1,92	1,23
3.30	2,48	1,85
2.48	3,78	2,47
1.98	4,35	3,08
1.65	5,21	3,70
1.42	5,60	4,32
1.24	5,95	4,93
1.10	5,92	5,55
0.99	5,66	6,17

As spacing between rows is increased, there is less shading on back rows, especially at the end of the day, and therefore more energy will be produced. However, for a fixed area, the bigger the distance mentioned, the less rows will fit. The result obtained is lower than the specified by the IDAE, which for the selected tilt was 2.4m.

6. Conclusions

The main conclusions from the demand analysis are:

- Annual demand for Leganés is 8.7GWh and for Colmenarejo 858.5MWh, accounting for 55.6% and 1.9% of the university's total demand respectively. The platform used to download all data proved troublesome. It consisted of a remote server that worked slowly and files had to be exported one by one. Once results were obtained, those that were deemed erroneous for Colmenarejo (negative values, outliers and Nan) were erased to work with a more reliable set of data. Because of this, the demand data throughout the three years decreased more than usual, as all false data was changed for 0 value.
- To cover demand of Colmenarejo (858.5MWh), a system of 98kW, with a capacity factor of one, working all 8760 hours a year would do. Considering a capacity factor of 0.16 (average in our system), to cover all this energy with PV, a system of about 610kW. For Leganés, dividing its consumption by the hours a year and the same capacity factor, a capacity of 6.2MW can be expected.
- From the boxplots a conclusion drawn is that both samples (Colmenarejo and both) are skewed, not symmetric. Results give an estimation of night consumption around 45kWh for Colmenarejo and 600kWh for both. Faults in data sample for Colmenarejo are still found, as extreme values are found. Maximum hourly consumption is around 500kWh and 3MWh for Colmenarejo and the combined case, respectively.
- Annual demand in Leganés is seen to fall through the years. This is a reflection of the energy saving measures taken by the university. It can be expected a descending trend through the years to come, which should be accounted for when sizing an optimal PV system. In Colmenarejo, from 2017 to 2018, consumption has risen. Despite this, it is expected to fall through the years to come, which again must be thought off when selecting the system's capacity.

From the generation analysis, it is concluded that:

- The different PV systems yielded expected performance ratios, ranging from 0.6-0.8. Only in one case is the PR not inside this range, in the Alfredo di Stephano's sport centre, with a value of 0.59, which is explained by the shading caused by the auditorium. In addition, capacity factor for the installed systems was around 14-18%, again close to the typical values for such systems as no production happens at night.
- For Leganés, only buildings Betancourt, Juan Benet, Torres Quevedo and the sports centre were suitable for installation, as the rest had tilted rooftops or could not be reached. In Colmenarejo, the major part of the installed capacity was seen in the extra plot; around 5.5MW. All 3D files needed patience and effort, SAM's 3D tool proved to be a slow method of obtaining results. The use of the self-shading section, combining with optimizing macros, was discarded as it gave a

less precise results of the shading loss factor by not taking into account buildings and other objects.

- A total of 1.17MW can be installed in Leganés, and 9.8MW in Colmenarejo. These values are limited to SAM's precision. Issues where found when designing a 3D map of the chosen site. In addition, partial shading of PV modules was not calculated for systems as big as the ones simulated here. If this capacity was installed for each individual campus, a PV load penetration of 17.4% would be achieved in Leganés, with 63.7MWh of excess energy. In Colmenarejo, these values would go up to 72% and 12.4GWh as the system is greatly oversized. Direct capital cost, including cost for panels, inverters and installation, would be 2.2 million € for Leganés and 11.7 million € for Colmenarejo.
- Looking into consumption of each building in Leganés, if 1.17MW are installed there, each building could self-consume its generation, as in Getafe. This would reduce transmission losses. It must be noted that in Colmenarejo this will not be considered, as the best location for the PV system is the extra plot, which would be considered an associated generation system.
- The definition of full self-consumption given reflects the potential the available locations have of reaching generation values similar to their consumption. For Colmenarejo, installing a 600kW system could generate values close to its demand (yearly); similar results to the one calculated previously in this section. The renewable penetration achieved would be of 40%. On the other hand, it can be seen that Leganés, due to its high demand and smaller available area, cannot achieve this. From simulations from SAM, it is predicted that 6.17GW would be needed to generate as much as it is consumed. This leaves an extra 5MW to be installed somewhere else. If both campuses were combined, a total of 6.77MW would be needed, with a penetration of 44.7%, meaning self-consumption is feasible for the combination.
- As despite installing such capacity that meets demand, PV penetration only reached 44.7%. This reflects the nature of renewable energy. Such sources depend on weather; sun, wind rain. Therefore, in this case, demand is not satisfied through the designed system, as a part of generation is lost as excess and at night no production happens.
- From statistical analysis of full self-consumption systems, it can be concluded that at least half the year the PV panels are not producing energy, as the 50th percentile equals 0. On the rest of the hours, there is generation, where the value for energy produced rises quickly, making for a more dispersed data over the median. In addition, both systems have many outliers, as once summer is reached and radiation is at a maximum, more energy is generated, which compared to the 50th percentile, zero, they are seen as outliers.
- To achieve remuneration of excess, installed capacity is limited at 100kW. In such case in Colmenarejo 14% of the energy fraction would be self-consumed, with a total excess energy of 11.4MWh. For Leganés, no excess of energy would be seen, and a self-consumed fraction of 1.57% would be achieved.

- It is concluded that tilt angle could be varied through the year. For the extra plot inn Colmenarejo, two different values would be used; 20º from April to September and 40º through the rest of the year. This would leave us with an annual energy generation of 7.48GWh compared to 7.28GWh obtained with a fixed tilt of 35º.
- Row spacing from SAM's simulation turned to be optimum for a value of 1.24, in contrast with the minimum calculated from [24], 2.4m. This difference can be due to the absence of partial shading losses in SAM's analysis.

Batteries pose the opportunity of making the most out of the PV system, energy wise. From the data obtained from the Matlab script it is concluded that:

- Leganés on its own would be able to reduce grid injections by 36.7MWh with an installed power capacity of 500kWh. Although this would only account for an increase in PV penetration of 0.4%, this is due to the size of the total demand.
- If both locations are combined, simulating for a power capacity of 3MWh, grid injections will be reduced 1GWh approximately. This would increase PV penetration to 63% (10% increase). Two battery banks of 1MWh should be installed in Colmenarejo, and 1MWh in Leganés.

The decision on whether batteries should be installed must be taken after an extensive economic report is developed.

When deciding what capacity must be installed for Colmenarejo only, one must take into account how the load is expected to develop. Despite the increase observed from 2017 to 2018, it is expected a decrease in energy consumption for the years to come because of energy efficiency measures taking place. Hence around 575kW should be installed for Colmenarejo, though the economic analysis should be performed to obtain the NPV of this case and the remunerated case, to see if installing only 100kW is more profitable because of the benefits for the energy injections.

For Leganés on its own, a full installation of 1.77MW should be performed, as generation would not exceed demand. As the difference between the two is big, no need to undersize the system to match the decrease in demand.

If both campuses could share generated energy, the recommended installed capacity would be as well lower than the one obtained from the full self-consumption results (6.77MW). An estimation of 6.2MW should be installed, generating 8.7GWh. This would mean that the extra plot in Colmenarejo would not suit on its own for the total PV system and installation would be required in other places. If demand is estimated to drop further on, then a smaller DC/AC ratio could be selected, to allow for the degradation of panels to reduce output power and match demand in the years to come.

7. Future work

This project was an energy analysis of both campuses. The battery analysis was a preliminary work to estimate the benefits obtained from their installation. To further complete the results obtained, the next should be developed:

- In depth economic analysis for all scenarios, and final recommendations. Cost for energy bought from the grid, following access tariffs and pricing periods according to the university’s contract. This will provide better a review of the project, allowing the team to take a well-informed decision and get the most out of the investment.
- Improve battery simulations taking into account battery discharge time, degradation and maintenance. This will give a more accurate result of the impact batteries can have on the system.
- Peer to peer market analysis. With some of the cases, the excess of energy could be sold to other consumers, improving profitability and increasing PV penetration.
- Tracking systems should be considered for Colmenarejo’s extra plot, as the available space would allow for such technology, and the improvement in generation would be notable.

8. References

[1] “Indicators - Nordic Energy Research,” Nordic Energy Research, [Online]. Available: https://www.nordicenergy.org/indicators/.

[2] “IRENA - International Renewable Energy Agency,” [Online]. Available: https://www.irena.org/.

[3] “Enerray,” [Online]. Available: https://www.enerray.com/blog/mena-solar-energy-market.

[4] “Lazard,” 2019. [Online]. Available: https://www.lazard.com/perspective/levelized-cost-of-energy-analysis-100/.

[5] “Solargis,” [Online]. Available: https://solargis.com/.

[6] “Physics Forums | Science Articles, Homework Help, Discussion,” [Online]. Available: https://www.physicsforums.com/.

[7] “The Permaculture Research Institute,” [Online]. Available: https://permaculturenews.org/2015/10/23/charting-the-suns-motion-in-relation-to-your-home-and-permaculture-site/.

[8] “TeachEngineering.org,” [Online]. Available: https://www.teachengineering.org/lessons/view/cub_pveff_lesson01.

[9] “BibLus,” [Online]. Available: http://biblus.accasoftware.com/en/photovoltaic-systems-what-are-they-how-do-they-work/.

[10] “Suncyclopedia,” [Online]. Available: http://www.suncyclopedia.com/en/solar-cell-the-basic-unit-of-a-solar-power-plant/.

[11] “PV Performance Modeling Collaborative,” [Online]. Available: https://pvpmc.sandia.gov/modeling-steps/2-dc-module-iv/diode-equivalent-circuit-models/.

[12] “Seaward Group USA,” [Online]. Available: http://www.seaward-groupusa.com/userfiles/curve-tracing.php.

[13] W. Shockley and H. J. Queisser, Detailed Balance Limit of Efficiency of p-n Junction Solar Cells, 1961.

[14] P. Sathyanarayana, R. Ballal , S. Lakshmi y K. Girish , «Effect of Shading on the Performance of Solar PV Panel,» *Energy and Power,* vol. 5, pp. 1-4, 2015.

[15] M. Vujacic, M. Srndovic, M. Hammami and G. Grandi, “Evaluation of DC voltage ripple in single-phase H-bridge PWM inverters,” in *IECON 2016*, 2016.

[16] C. Babu, B. V. Prasanth and P. Sujatha, “A Review: Significant of RES for 21 st Century and Cost-Efficiency Based SWT/ Solar Interconnection Topologies Pertaining to Micro Grids,” 2018.

[17] E. Kabalci, “Maximum Power Point Tracking (MPPT) Algorithms for Photovoltaic Systems,” in *Energy Harvesting and Energy Efficiency*, 2017, pp. 205-234.

[18] «Bypass Diodes in Solar Panels and Arrays,» *Basic Electronics Tutorials,* 2019.

[19] K. Zipp, «Why array oversizing makes financial,» *Solar Power World,* 2018.

[20] “Ministerio de Hacienda,” 2017. [Online]. Available: https://contrataciondelestado.es/wps/portal/!ut/p/b0/04_Sj9CPykssy0xPLMnMz0vMAfIjU1JTC3Iy87KtUlJLEnNyUuNzMpMzSxKTgQr0w_Wj9KMyU1zLcvQjc4K1w0Mt3HPCkh0DvY1CXNMi3Cu1HW1t9Qtycx0Bwz3Hgg!!/.

[21] “Informe Energético UC3M 2018,” 2019.

[22] “https://us.sunpower.com/,” [Online].

[23] “NREL - System Advisor Model (SAM),” [Online]. Available: https://sam.nrel.gov/.

[24] IDAE, “Pliego de Condiciones Técnicas de Instalaciones Conectadas a Red,” 2011.

[25] Meteonorm, “Meteonorm,” [Online]. Available: https://meteonorm.com/.

[26] EU Science Hub, “PVGis,” [Online]. Available: https://ec.europa.eu/jrc/en/scientific-tool/pvgis.

[27] “Statistics Canada,” [Online]. Available: https://www150.statcan.gc.ca/n1/edu/power-pouvoir/ch12/5214889-eng.htm.

[28] “PVinsights,” 2019. [Online]. Available: http://pvinsights.com/RetailerPrice.php.

[29] Solaranna, “0Bills | Wind and Solar,” [Online]. Available: https://zerohomebills.com/product/tesvolt-lithium-battery-storage-500-kwh-tlc500/.