ET3036TU

Project Design of Sustainable Energy Supply
Project Report

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Group I

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Abstract

This report describes a micro-grid in both externally connected and islanded variants. Using models, a situation involving a combination of sustainable energy sources, a battery or a grid connection and a variable load pictured by a set of households. By describing the methods used and discussing whether sustainability, affordability or reliability is more important, a thorough picture of the situation is given. Furthermore a simulation is created and checked with further data years.

For both islanded and grid-connected systems, the goals set in the beginning are met. A thorough discussion is made on choices which affect sustainability and affordability. While not fully sustainable, the conclusion is believed to be feasible in reality.

1 Introduction

Access to energy in a fair and equitable manner is paramount to achieve long-term sustainable development. With an ever-growing demand for electricity consumption worldwide, the capabilities of today's centralized power systems might fall short of the requirements of future energy markets. Microgrids offer a potential infrastructure that can help facilitate the transition to a more decentralized approach in constructing power grids, which could drive down the expenses needed through better matching supply and demand, whilst increasing the underlying reliability and reducing the overall environmental impact.

Current trends show a susceptible shift towards an energy market in which the share of renewable energy will drastically increase. Even more so, it is interesting to explore whether every consumer in Europe will produce its own energy, or would be connected to one major renewable energy system. For this project, a microgrid setup is introduced, explored and evaluated to ultimately converge to the best solution. In this research, either an islanded microgrid or a connected microgrid will result in the most reliable, sustainable and affordable system.

In this report the model, control generation and storage is described in order to supply the load for a given group of household. This includes several key sub-objectives, namely:

- Selecting the appropriate models and parameters for the simulation
- Designing a controller which works for storage, generation and demand
- Selecting and sizing several generation options, while making sure to keep track of grid-connected and islanded connections
- Using historical data for design and analysing the performance with more recent data

To achieve these goals, several tools are given. These include a powerpoint with all intermediate steps, a custom Simulink model library, consumption data, weather data and relevant literature. To explain a little more about this project in this introduction, some relevant literature will be used.

2 Data Analysis

2.1 Supply and Demand Analysis of Training Data

The expected surge of energy demand associated with economic growth, alongside the ongoing development and integration of renewable energy sources calls for a "paradigm shift", in which the volatility of such resources is handled accordingly [8]. To better understand the underlying problems the model might need to attempt to solve, an in-depth analysis of the given 3-year dataset was carried out. For the first iteration, details about wind speed, irradiance, temperature and the load demand were given for each day of the year (2013, 2014, 2015). Visualisations of the data-points are provided in Figures 1, 2 and 3.

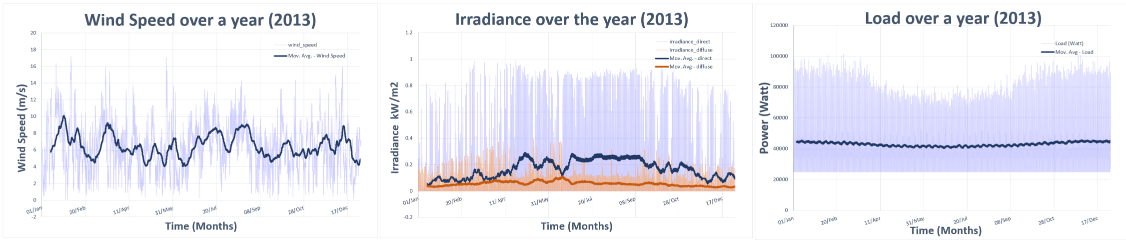

Figure 1: Dataset visualisation for the year 2013

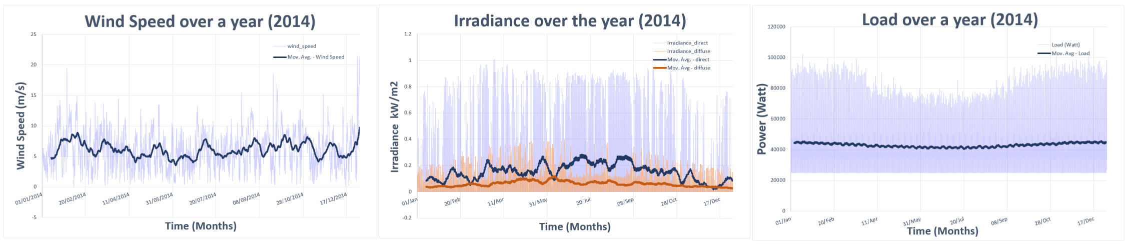

Figure 2: Dataset visualisation for the year 2014

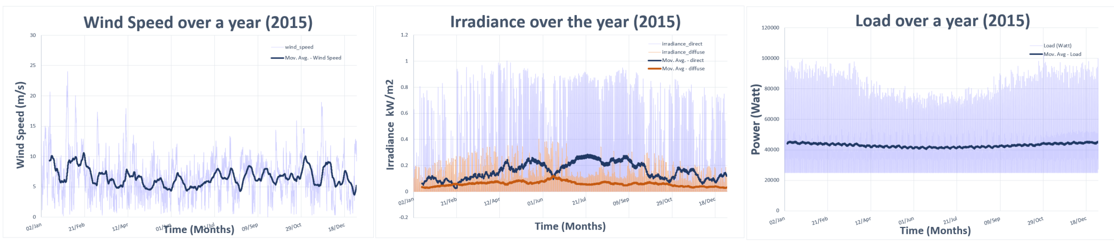

Figure 3: Dataset visualisation for the year 2015

It is important, especially for renewable resources (in this case, wind and solar), to carefully analyse and formulate the intrinsic variability, such that the system requirements are constructed as accurate as possible.

1. **Characteristics of wind speed**
   Looking at the graphs above (Figures 3, 4 and 5), no real pattern can be identified for the wind speed, as it tends to vary significantly on a yearly basis. This can be observed through the variance in the datapoints over the 3-year dataset in Table 1.

   From the table above, it can be seen that the highest wind speed was recorded in 2015, alongside the highest variance and mean in the data. The average wind speed of the given

Table 1: Parameters of the wind speed distribution. All parameter values are in m/s.

3-Year Dataset				
Year	Minimum	Maximum	Mean	Variance
2013	0.016	17.246	6.45	8.74
2014	0.002	21.44	6.15	8.81
2015	0.024	24.03	6.61	10.99

years is around 6.5 m/s, which is relatively high. Due to the pressure difference above land and water, wind speed is typically much higher near the sea.[11] This suggests that the 160 households are located near the sea, which makes sense because of Istanbul's maritime position. Offshore wind turbines might be a potential solution to ensure a consistent energy supply throughout the year.

2. **Characteristics of irradiance**
   It can be seen from the charts that the distribution of the irradiance, both direct and diffuse, follows a Gaussian-like spread. This is expected since there is more sunlight during the spring and summer seasons. One particularly interesting aspect to notice is the fact that during those seasons, there are occasional dips of irradiance. This could be due to Istanbul's marine location, which results in frequent fog, limiting the city's daylight hours.[1]

3. **Identifying load patterns**
   The load profile gives important insights to power generation companies regarding how planning should be done to accommodate the needs of all its consumers. The load varies on a per-customer basis, yet other factors such as temperature or seasons have a more substantial impact over the load distribution. From the three charts above, it can be seen that the load follows a bathtub-like curve. This is expected, as at the beginning and ending of the year, generally, more power is used for various season-specific demands (e.g. temperature control, increased electricity consumption for appliances etc.). The microgrid needs to be able to generate a stable energy supply for an average of 45kW to consistently comply to the energy demand of the 160 households per year. However since the maximum demand load is around 120 kW and is reached each day throughout a year for approximately 20 minutes, the decision was made that a safety factor of 2 should be taken into account and therefore the final design should be able to generate an energy supply of 90kW.

2.2 Supply and Demand Analysis of Test Data

Having the test dataset released, the team began a thorough analysis to characterize the new samples to be added to the dataset. This analysis was rather crucial as it could help affirm or deny the assumptions and hypothesis drawn from the initial dataset.

Some of the data from the test set differs quite a bit from the data in the training set. It is of utmost importance to have a reliable model even for this different dataset. This section will give an in depth analysis of the data that was given for the year 2017 and 2018 (Figures 30, 31).

1. **Characteristics of wind speed**
   In figure 4 below, a comparison is given for the wind speed over the years, visualized as boxplots. There are two important points to notice, namely that the maximum wind speed in both 2017 and 2018 lies in-between those of the training data (2013, 2014 and 2015). Furthermore, the average wind speed in 2018 is actually the highest of all years. In this year, the mean wind speed is almost 9% higher than the lowest mean wind speed in the training data. As the model has been trained to be able to achieve the load demand with lower average wind speeds, it would be expected that this would not cause any problems with the test data.

2. **Characteristics of Irradiance** Compared to the training data, the test data does not differ much for the irradiance as well. Most notably, when looking at figure 5 is that, overall, 2018

has the lowest mean irradiance level of all years. The difference with the highest mean in the year 2013 is roughly a 7% decrease. Even so, with the higher mean wind speed in this year, load demands should still be able to be met.

3. **Load demand changes** Identifying the demand discrepancies by comparing the training and test data is rather important as the system needs to constantly deliver power to its end consumers. If the system was built to accommodate lower demands than found in the test data, issues such as load curtailment can appear more often, However, this is not the case in this scenario. As can be seen in figure 6, the load demands in 2017 and 2018 are lower than in the training data years. Even though it's only a slight decrease of less than 2%, the model should be fully equipped to work with this load demand. Furthermore, the load values are on average lower than the ones found in the training set, as can be observed in Figure 7.

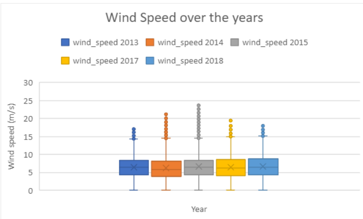

Figure 4: Boxplot comparison of wind speeds over the years

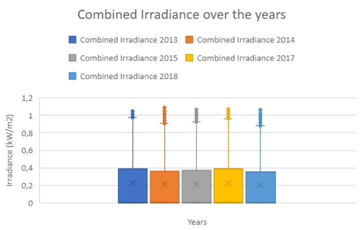

Figure 5: Boxplot comparison of irradiance levels over the years

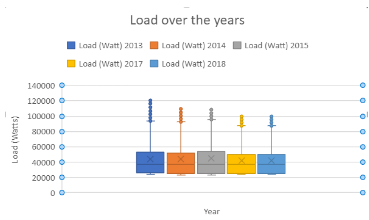

Figure 6: Boxplot comparison of load demand over the years

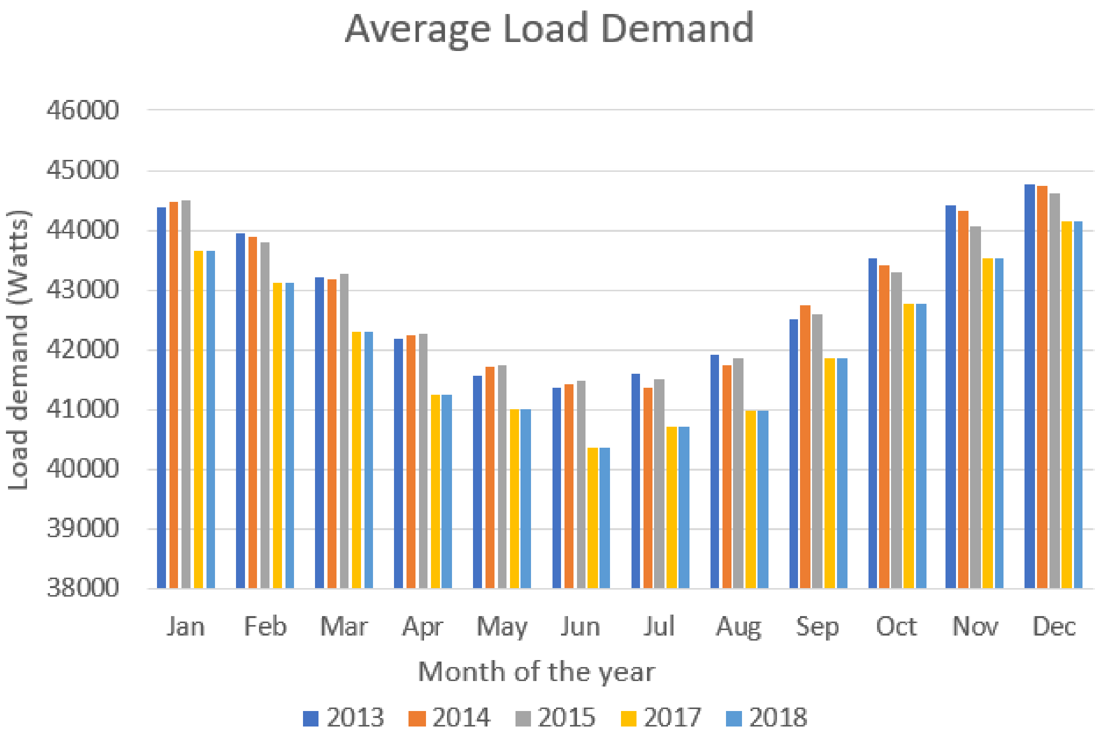

Figure 7: Average load demand for all dataset years.

3 Methodology

The intent of this section is to describe the methods conducted to build and simulate both the external grid-connected model as well as when the system falls into an islanded model. First, the method of simulation will be described. Then the model build for the microgrid to operate in grid-connected and islanded mode should be established. Additionally, a cost analysis is described to determine which option could potentially give a desirable trade-off between sustainability, affordability and reliability.

3.1 Simulation Mode

An important factor in performing the simulations is the simulation mode. Therefore, two simulation modes are considered: discrete and phasor. In discrete simulation mode, the simulator calculates each step in time based on the time steps specified (which in the project case is 0.005 sec). In phasor mode, the simulator uses voltage and current phasors. These result in less complex linear algebraic equations and is therefore faster than the discrete mode, when simulating over a longer time period. However, phasor simulation only works at one certain frequency at a time, as that is how the phasors are defined.[5] In this case however, only one frequency is being used, and as such this disadvantage is not relevant.

In order to determine which of the two simulation modes are going to be used during the rest of the project, a phasor simulation and a discrete simulation are conducted for the data of the year 2014. These simulations will be conducted over a time period of one day (86400 seconds).

Figures 8 and 9 show the difference between simulating between discrete and phasor mode. From

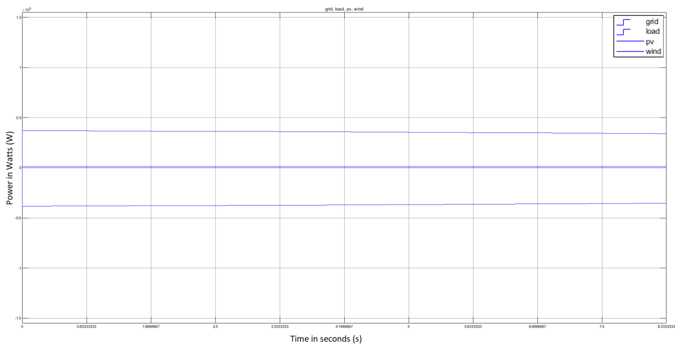

Figure 8: Discrete Simulation 2014

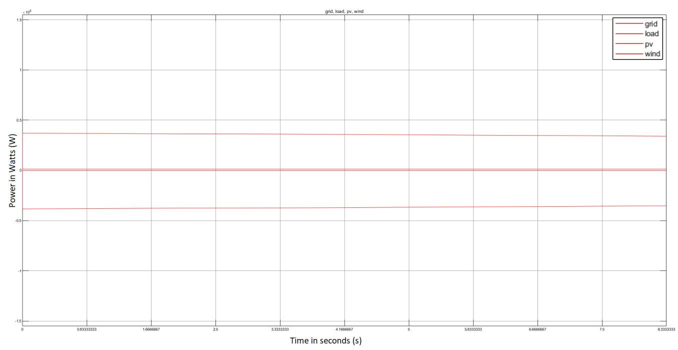

Figure 9: Phasor Simulation 2014

this figure it can be seen that the outcomes of the simulations are nearly the same. The discrete simulation shows the small step size calculations conducted and is therefore more detailed than the phasor simulation, which extrapolates the data points to a fluent line. Therefore, a trade-off between speed and precision is made. Considering that the main simulations will be conducted over a time period of a year, the simulation speed will have the priority over precision, since the differences in accuracy are less than approximately 100 Watt, which is an insignificant amount of power considering that the power over a year has an average of 45000 Watt.

3.2 Components

Wind Turbines

Since the average wind speed throughout a year is roughly 6.5 m/s, this would correspond with the coast of Istanbul as can been seen in Figure 10. For this area both offshore and onshore

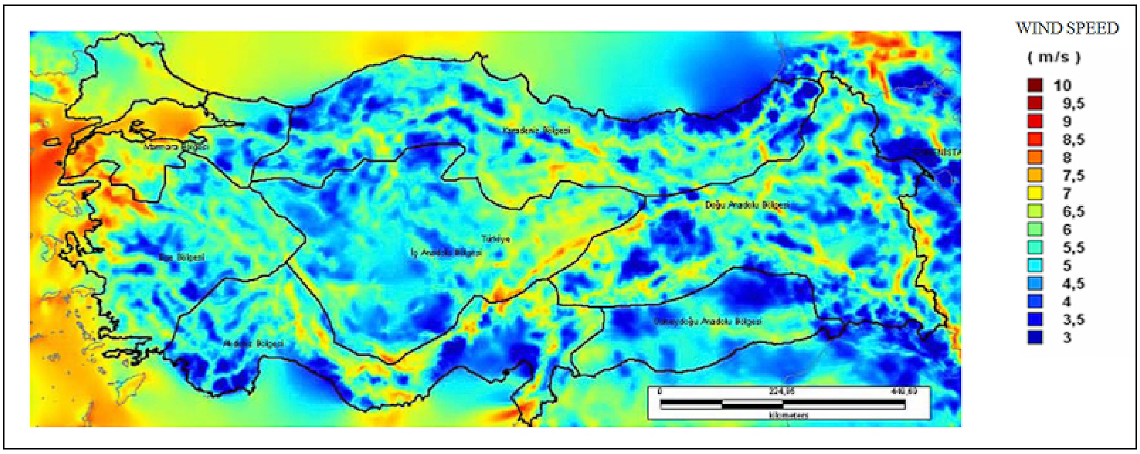

Figure 10: Wind map of Turkey - Source: Mustafa Çalışkan, 2007, Wind Energy Potential of Turkey, EIE , p:11, Ankara.

wind turbines could be used. However, the decision was made to only make use of onshore wind turbines, since the rated power that should be generated over a year should be approximately 90kW. An offshore wind turbine, with a general capacity of 12 MW, would be too overpowering or overwhelming.[10] Furthermore the offshore wind turbine is also significantly higher in expenses than onshore wind turbines. Therefore only onshore wind turbines will be considered.

A combination of the load data given and the requirements described in the introduction, provides an approximate estimation of which turbines would be suitable for the microgrid. To properly evaluate these options, four onshore wind turbines were selected and evaluated as can be seen in A.3. First a life-cycle analysis and cost analysis was made for all four the wind turbines. Then the criteria of the turbines were compared by means of a Harris Profile. As a result, it can be deduced that the Fuhrländer FL 30 wind turbine would fit the microgrid model the best.

The Fuhrländer generates around 4.7kW and costs €231828.64 per turbine. Additionally, this wind turbine has a cut-out wind speed of 25 m/s.[4] Therefore it will not influence the performance of the wind turbine too much if it reaches the maximum wind speed recorded in the historical data, 24.03 m/s.

Solar panels

Solar panels must be used in the microgrid to provide a power output that will keep the batteries charged during high power demand and/or low wind speed events while also ensuring the sustainability of the microgrid. Due to the similarity of most solar panels, only the efficiency and total surface area may vary.

The criteria for the solar panels included the costs and the amount of solar panels needed if the microgrid would solemnly exist of solar panels. By conducting the same methods for the decision for the wind turbine as can be seen in A.4, the JA SOLAR 365WP panel seems to fit the microgrid the best. This solar panel has an efficiency of 20.1 % and costs €145.00 per panel.[6]

Batteries

An energy storage with a capacity of 500 kWh is added to the islanded model. As batteries with such a high capacity are hard to find on the internet, an estimation is made with a battery with a capacity of 233 kWh and 100 kW power. On the website 0Bills they sell this battery [1].

3.3 Cost Analysis

In the cost analysis there are decisions made based upon the components chosen before. The costs are shown and small calculations are done to finalize the image of affordability. Note that the battery is not implemented in the Grid connected model.

Batteries

Making an estimation where the price of this battery is roughly 2.14 times lower than the battery of 500 kWh, the total investment of a battery is roughly €324.900. The capacity of the battery could potentially be reached when too much energy is generated. This potential energy is therefore thrown away. When adding a controller, energy generation can be adjusted and therefore losses can be avoided. The energy is generated by either solar panels, wind turbines, or the diesel generator.

Especially for the islanded model, it is important to come to an agreement of the three dilemma's. Affordability, reliability and sustainability all need to find an equilibrium. First of, the battery is very expensive, which takes a toll on the affordability but increases the reliability of the model. Additionally, wind energy and solar energy require a big investment, these energy sources are sustainable. However since they are not able to supply the 160 households of a steady energy supply as shown by the historical data. Thus, it takes a toll on the reliability aspect of the model. Furthermore, the diesel generator is more affordable and reliable, but not sustainable.

In order to properly account for all the costs made by each subject, a yearly cost price has been calculated. As the battery previously mentioned costs €324,900 in total, an estimated of 10 year lifetime will make a yearly cost of €32,500.

Wind turbines

Investing in wind turbines is very expensive and lifts the total investment to a higher level. For the cost analysis, an assumption was made where the power generated, which was 90kW, is produced by only the wind turbines. The calculations for the cost analysis can be found in A.3.

As a result of the calculations, the power generated per wind turbine for the Fuhrländer FL30 is 4.7kW, the amount of wind turbines needed will be 20 and the total costs will be €240000.00. If a lifetime of 20 years is assumed for the wind turbines [9], then the costs for the wind turbines per year will be approximately €12000.00 per year, excluding the maintenance costs.

Solar Panels

For conducting the cost analysis for the solar panels, the assumption was also made to determine the costs if only the solar panels were taken into account as the solemn supplier of energy.

The results of the calculations (which can be found in A.4) are as followed. The amount of JA SOLAR 365WP solar panels needed is 1095. The total costs for these solar panels will be €158744.66. If once again a lifetime of 20 years is assumed, then the costs for the solar panels per year will be approximately €7937.23 per year. This energy might be very cheap, but only during sunlight hours does it produce energy, thus a secondary form of energy generation is needed.

Generators Both solar energy and wind energy aren't the most reliable energy systems. As solar energy only produces energy during the day and wind energy will produce significantly less energy with lower wind speeds. In order to account for this in the external grid is connected to an infinite grid. In case the microgrid is disconnected from the grid, which in this report is referred to as islanded mode, a diesel generator is be added. The controller will make sure to only use the

[1] BYD 88-C230 HIGH VOLTAGE 233KW COMMERCIAL SOLAR BATTERY PACKAGE

generator when needed. In terms of costs for this generator (note: also operation/maintenance costs), it is decided that the generator would costs the same amount the grid operational cost + installation, thus removing them both out of the cost analysis.

3.4 External Grid-connected System

In this section the external grid-connected system will be described. This system does not need any energy storage, as it can cover the load demand through the external grid. In this section, the model, components and their pros and cons will be described.

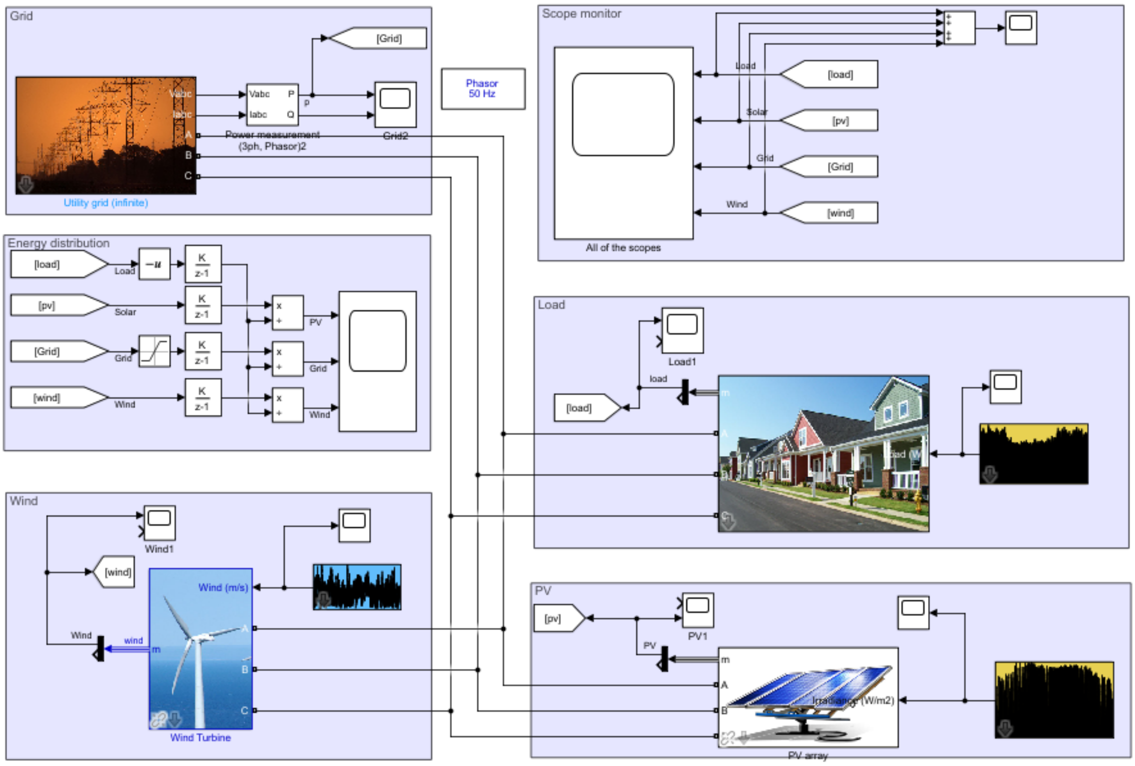

Figure 11: External Grid-connected system model

Figure 11 is a connected grid with a separate bus. The solar energy, wind energy and the load from the households are connected to this bus. These connections together form the bus. Scopes are added to the wind energy, solar energy, load and the grid. The given training data is from the years 2013, 2014 and 2015. For each scope, only the active power line is added to it. Since reactive power does occur at the grid, but in this system/model is not accounted for. It also does occur at the load, but the power factor is set to 1, so in total, there is no reactive power.

3.5 Islanded System

In this section, the Islanded system will be described. This system works autonomously and thus needs energy storage to be able to fill load demands when renewable energy is not sufficient. This section will also include the model.

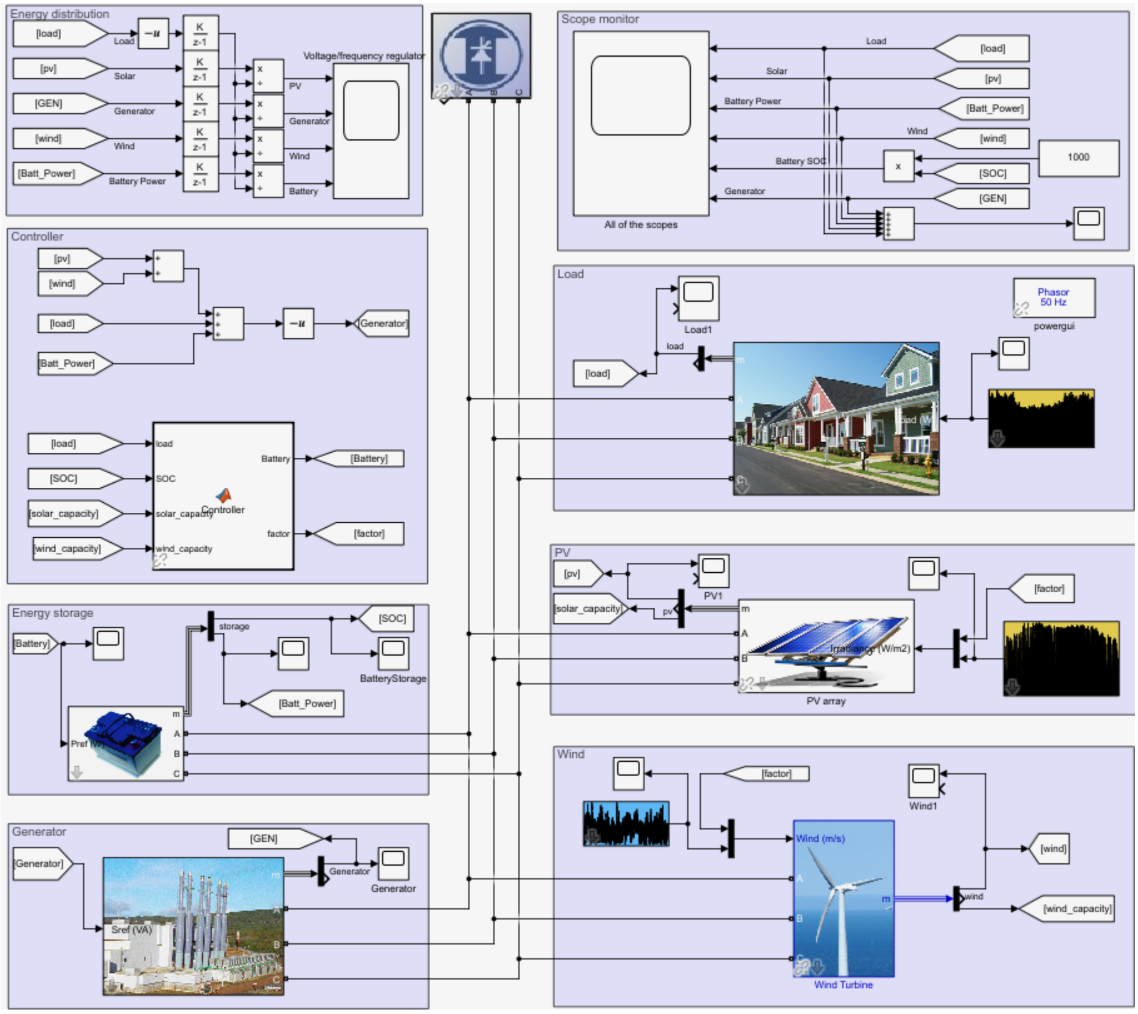

Figure 12: Islanded system model

When the grid-connected microgrid switches to islanded mode, the power flowing from the grid is cut off. Therefore the microgrid will suffer a significant power deficiency due to the loss of the grid. Insufficient energy generation will cause outages for the load and will lead to energy losses. In order to prevent energy losses as much as possible, the frequency of the microgrid should be regulated, which will be done by the voltage frequency regulator (Figure 12). Additionally a generator, energy storage and a controller are added to improve the reliability that a grid can give when operating in islanded mode. The functions of these components will be discussed in the discussion section.
As before, the subjects in this model have scopes with given data from 2013, 2014 and 2015. Also in this case, there is no accounting for the reactive power, it is set to zero.

4 Discussion

Once baseline models for the grid-connected and the islanded systems were established, the team realised that the complexity of both setups can increase significantly with each newly added functionality to maximize it's efficiency. The purpose of this section is to yield key insights and explain the reasoning behind the design choices made to create the final model. First, a more in-depth analysis of the training data will be performed, followed by separate sections tailored to each situation (on-grind and off-grid), entailing the reasoning behind the model architecture and the cost analysis adjacent to the design decisions.

4.1 External Grid-connected System

During the modelling of the External Grid-connected System, lots of choices had to be made. This section will detail the decision making process for these choices and elaborate on them further.

4.1.1 Associated Estimated Costs

Since renewable energy, such as solar and wind energy fluctuates frequently, insufficient or too much energy might be generated relatively to the required load. For the grid-connected model, this should not cause a problem. When there is an abundance of energy being generated, the extra energy will flow back into the grid, while in cases of insufficient generation, the grid is able to supply the missing energy.

It is expected that an infinite grid connected system will cost less, since the energy that will be send back to the infinite grid, will be sold for the exact same price as produced.[2]

For consumers however, this method might be more costly, as being dependent on the grid means that the owners of the grid will be able to charge more.

4.2 Islanded System

This section will cover the decision making process of the Islanded system. This system is more complex due to added components, which makes the process a bit more difficult. As such, this section will elaborate on all the choices.

The functions of the added components to the islanded grid are as follows:

- The energy storage (battery) will store energy if there is more renewable energy than the load requires.
- The battery will discharge energy when there is not any wind or sun to produce the renewable energy needed for the load demand.
- The controller, curtails the solar panel and the wind turbine in such a way that production limits are defined in order to stop the energy storage from overflowing.
- The controller ensures that if the amount of renewable energy produced and/or energy storage does not supply the amount of energy needed for the load demand, that a generator is used to supply the amount of energy needed.

4.2.1 Associated Estimated Costs

Furthermore, to ensure that the energy storage does not overflow, constraints in renewable energy production and the diesel generator have been added. The controller also adds constraints to the

[2] This was discussed during the lecture of the course ET3034TU Solar Energy by Arno Smets on 1/12/2021

renewable energy sources by controlling the output power of these sources by means of a factor. Figures 14 and 15 present the schematics in which the constraints are made within the renewable energy sources.

Furthermore the controller has been programmed in such a way that the energy storage will only store energy whenever the renewable energy sources produce more energy than the load demands. Additionally, the generator only produces energy when both the renewable energy sources and the energy storage are not able to comply to the load demand. This way the households do not have to follow restrictions on the load when the microgrid is in islanded mode.

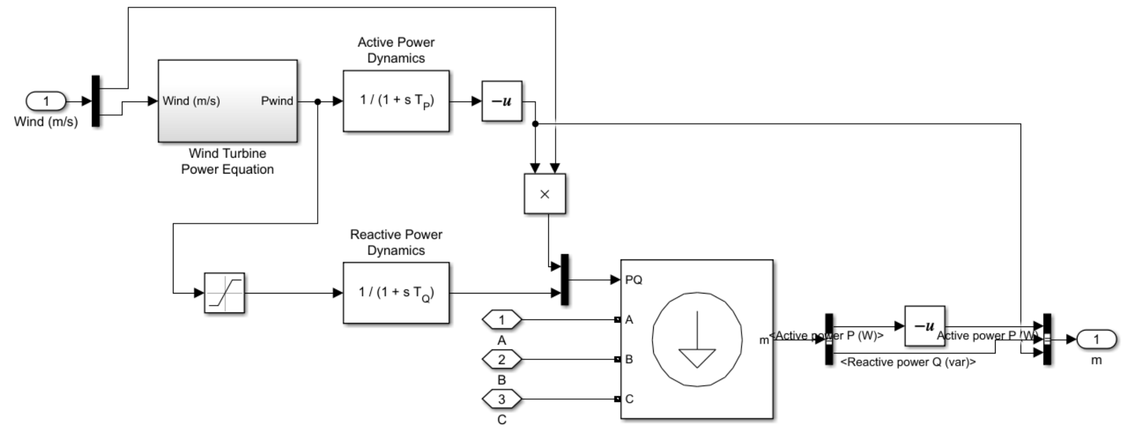

Figure 13: New Wind Turbine schematic

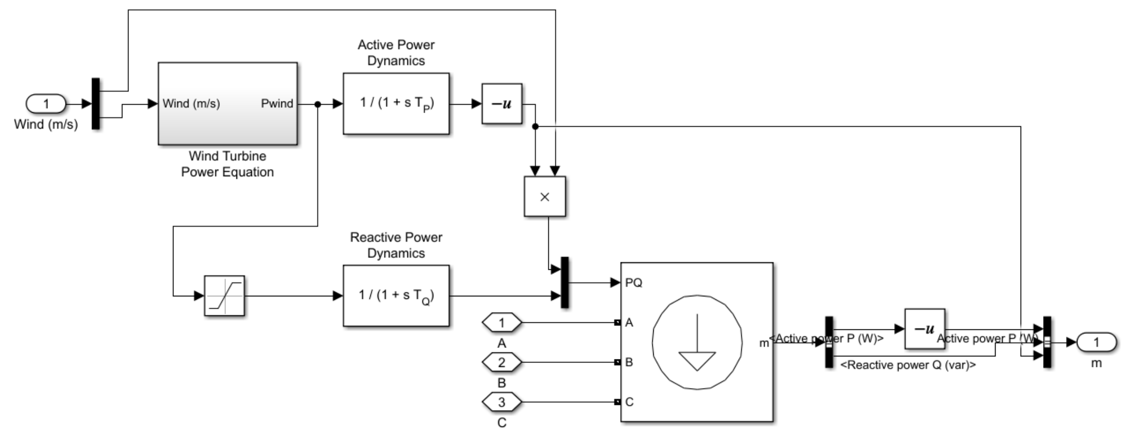

Figure 14: New Solar Panel schematic

4.2.2 Controller Design and Strategy

The code for the controller can be found under Appendix A.1. The purpose of the controller, as seen in Figure 15, is to properly manage the energy balance within the microgrid, while being optimized to make the most out of the renewable energy production installed. The algorithm decides, depending on the battery state of charge (SOC) to firstly (if $SOC < 89\%$ - first *if* statement) use the full power of the renewable energy sources to both accommodate the load and charge the battery, or (if $89\% <= SOC < 99\%$ - *elseif* statement) proceed to slowly decrease the rate at which the battery is charging and meet the load demand. If the battery is near-fully charged ($SOC > 99\%$ - *else* statement), the generation is calculated without taking into account the charging of the battery. Lastly, the *Battery* variable indicates how much should the battery charge or discharge to fully accommodate the load (after the solar and wind generation were taken into account). This way, the usage of the battery is kept to a minimum.

Moreover, the algorithm that controls the diesel generating unit was extracted out of the controller code to provide better clarity and separation of concern. This rather simple technique assures that the generator is engaged as little as possible. The logic can be found in Appendix A.2, in Figure 17.

As in the past decade the costs for small-scale renewable energy generation systems (i.e. solar and wind) have fallen far enough to make sustainable microgrids an economic reality, it is important to take into account the limitations in our research and opportunities for future work. Currently, we have optimized our controller to make achieve energy balance by engaging the generator as little as possible. Yet we have not taken into account peak-load reduction and control energy provision, which can selectively switch off the loads on a priority basis [7]. Furthermore, spot or options markets can be considered to reduce the energy prices for the consumers.

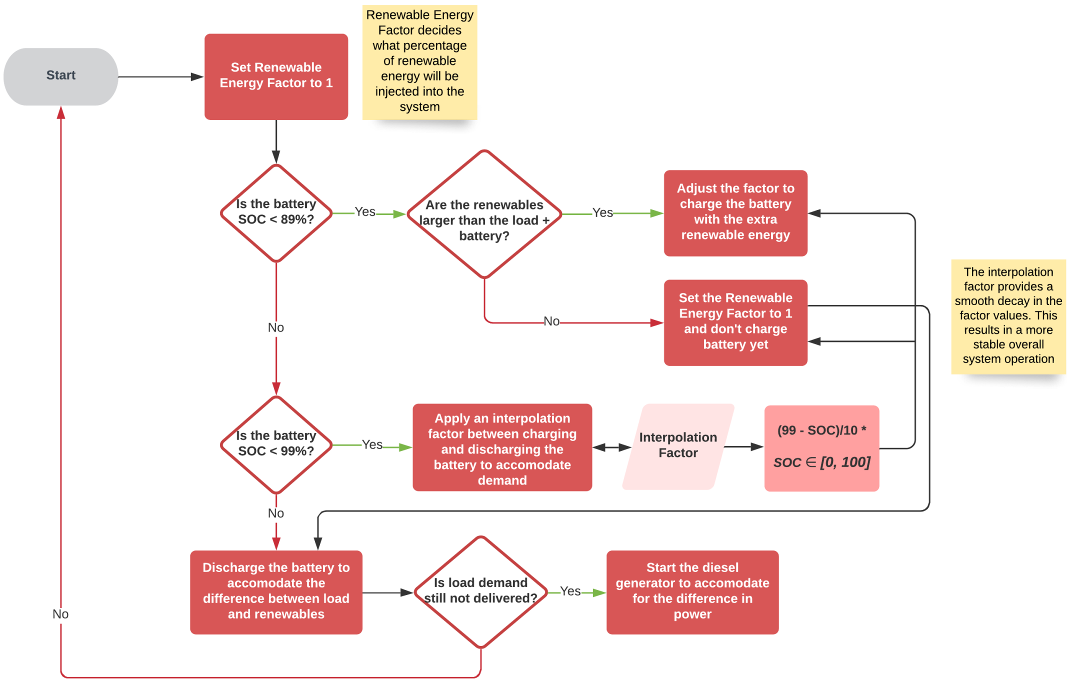

Figure 15: Flow Chart Diagram of the System Controller Design

5 Results

The purpose of the Results section is to summarize the data obtained from the simulations run by Simulink. The data is based upon the methodology as described in the Methodology section. Furthermore, a short explanation of all the results will be given.

5.1 External Grid-connected System

The goal of this section is to choose an option of energy sources which results in a balance between the three dilemmas (sustainability, reliability and affordability). How much energy each energy source is supposed to deliver is checked with different options, where the grid is supposed to deliver the least amount of energy. The combinations are made as followed:

Table 2: The chosen combinations for Solar energy (S) and Wind energy (W).

S/W comb. (%)	**Av. Grid (%)**	**Av. prod. (S/W) (%)**	**Cost of comb. (€)**
90/10	55	95/10	€ 95.435,10
10/90	36	11/94	€ 287.435,10
50/50	37	53/54	€ 159.686,17
30/70	34	31/75	€ 191.811,70
70/30	44	75/33	€ 127.560,63

From the table above the distribution of Solar energy (S) and Wind energy (W) can be seen. The average grid usage is shown as an indication of sustainability. If the grid is used less, then the renewable sources match the requirement of the load more, which makes it more sustainable.The average production of Solar and Wind energy is shown as a parameter of reliability, being close to its chosen combination means less fluctuations. Lastly the combination cost is shown as an indication for affordability. As can be seen, neither the cheapest nor the most expensive seems to be the best solution in terms of sustainability. In terms of expenses, when a lifetime of 20 years is estimated, the total cost per year is €9590.59. which is not a very high number, when this is divided by 160 households (€60 per year per household). Therefore, the option 30/70 is the most preferred. For the islanded model, 30/70 will be set and the test data will be run on this option. With this topology, a table has been created shown below.

Table 3: Combination 30/70 Solar/Wind energy distribution over the years.

Year	**Grid usage (%)**	**Production (S/W) (%)**	**Back to Grid (%)**
2013	28	30/86	44
2014	40	33/60	35
2015	31	33/81	47
2017	36	32/69	38
2018	22	29/104	56

The table shows that the grid usage fluctuates heavily, as there is no curtail. Thus when there is extra production all of it will be given back to the grid. When simulating this model, the back to grid percentages were found when changing the saturation block from UPPER limit to 0 and LOWER limit to -inf. This shows the amount of energy given back to the grid. When adding the grid usage and production of solar and wind together (-100%), the same number is acquired as the back to grid percentage.

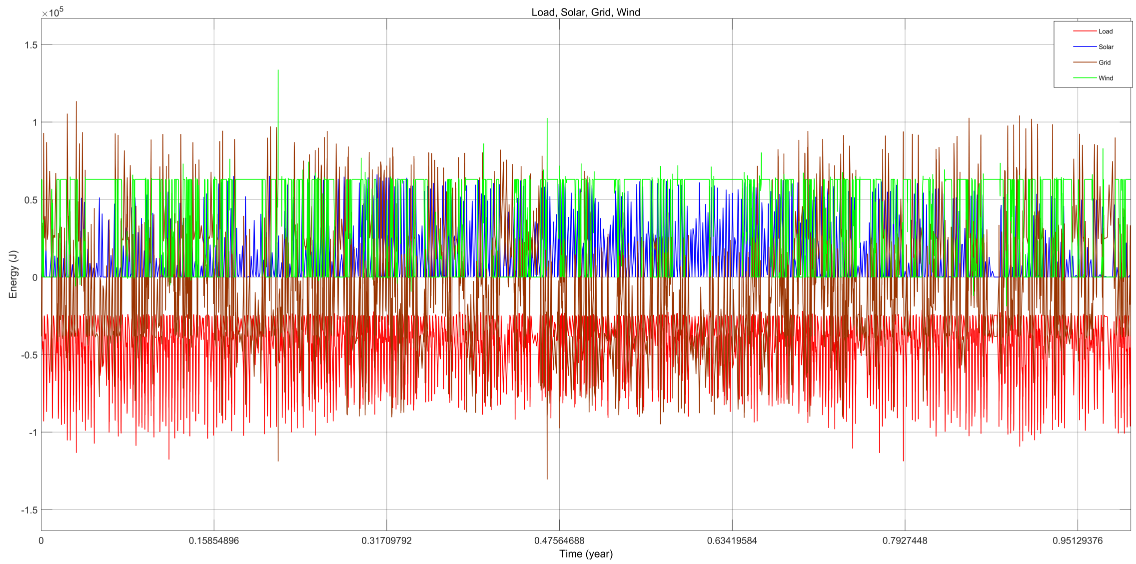

Figure 16: External grid-connected system 2013.

Figure 16 shows how the energy demand/supply looks with the configuration of 30/70 (Solar/Wind) for the year 2013. In the appendix, a graph can be seen for the islanded model of 2013.

5.2 Islanded System

The islanded model is more expensive than the grid, as the battery is expensive. The generator is not sustainable, thus a same sort of calculation as the table mentioned earlier has been implemented into the table below. Note that the combination of 30/70 is also chosen here, for all five years. This table can show the accuracy of the analysis.

Table 4: All 5 years for the chosen combination of Solar/Wind (30/70).

Year	**Prod. (Gen.) (%)**	**Prod. (S/W) (%)**	**Prod. (Batt.) (%)**
2013	15	23/67	-5
2014	15	28/48	9
2015	13	23/58	5
2017	16	26/53	6
2018	12	21/73	-8

The table above reveals that the energy production for solar energy is quite stationary. As for wind energy, it does fluctuate more. The generator however, does seem to be quite stationary. It makes sense that the production of solar and wind is now lower, as it can be curtailed by the controller. The production of a battery can be negative, this shows that the rate of charging is higher than the rate of discharging. Note that all these productions added together should roughly lead to a 100% (all numbers are rounded thus it differs a bit).

In terms of expenses for the islanded model, only the battery costs extra expenses to each household (compared to the external grid connected model). This leads to (32,500 + 9590) = €42,090 per year. Divided by the number of households being €263 per year per household.

6 Conclusion

As mentioned in the Introduction, the goals for this project are to successfully create two differently connected models and design an analysis that is reliable enough to use in more recent years. A comparison was performed between both models.

As could be seen from the Results and Methodology, the models worked properly to extract information for this project. It can be concluded that the external grid-connected model is less complex and less expensive, as less components are being used for a completely working model. A basic Islanded model would have an absence of reliability. To compensate for this reliability, the model needs extra components to increase this factor, making it more complex and expensive.

The analysis that has been created turns out to work properly and quite accurate. The years 2013, 2014 and 2015 are training data upon which an analysis and sizing is done. The years 2017 and 2018 are test data, testing the accuracy of this analysis. The islanded model shows a lot of fluctuation in the wind energy, this is due to the fact that it is often curtailed by the controller, thus lowering its production. The most important factor is the generator, which has a stationary usage every year. Thus knowing that its sustainability is also stationary.

The dilemma choices for sustainability, affordability and reliability is clear. The external grid-connected model was already reliable enough, no extra expenses are made to increase this reliability, thus saving on affordability as well. Making sustainability an easy task taking only some toll on affordability having a total cost of roughly €190.000 (See Results, €60 per year per household). The sustainability however is not the highest it can achieve. The grid still delivers roughly 34% of its energy, which is considered to be generated by a diesel generator. But when looking at the fact how much energy is given back to the grid (which is sustainable) and by making the assumption that this energy can be extracted again from the grid, it averages to 44% (See table with 'Back to Grid (%)'. Thus when using the grid, 44% of it is sustainable, leading to a total of 19% unsustainable energy consumption (Grid usage, generated by a diesel generator).

For the islanded model however, this dilemma was a lot more complex. The reliability was very low thus a generator and battery were added, taking a huge toll on sustainability and affordability respectively. Then extra expenses are made to increase sustainability. For this dilemma, the expenses are roughly €520.000 (as mentioned in the methodology, Battery + Solar panels + Wind turbines). This number might look high, but when considering solar panels and wind turbines with a lifetime of 20 years and a battery with a lifetime of 10 years it costs €263 per year per household (See results). Since energy bills are paid per month, this would be €22 per month per household. So it is indeed feasible and financially possible to have an islanded micro-grid as an option, while being sustainable, reliable and affordable, since only an average of 14.2% of the energy generated is unsustainable.

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List of Figures

A Appendix

A.1 Controller

The code for the controller designed can be found below.

```
function [Battery, factor] = Controller(load, SOC, solar_capacity, wind_capacity)
   factor = 1;
   battery = 100 * 1000; % 100 kW

   if SOC < 89 % full power
      factor = factor_caclulator(solar_capacity, wind_capacity, battery, load);
   elseif SOC < 99 %smooth decay
      interpolate_factor = (99-SOC)/10;
      factor_alpha = factor_caclulator(solar_capacity, wind_capacity, battery, load);
      factor_beta = factor_caclulator(solar_capacity, wind_capacity, 0, load);
      factor = interpolate_factor * factor_alpha + (1 - interpolate_factor) * factor_beta;
   else % curtail
      factor = factor_caclulator(solar_capacity, wind_capacity, 0, load);
   end
   Battery = -((wind_capacity + solar_capacity) * factor + load);
end

function [factor] = factor_caclulator(wind_capacity, solar_capacity, battery, load)
   load_battery_demand = -load + battery;
   if wind_capacity + solar_capacity > load_battery_demand
      factor = load_battery_demand/(wind_capacity + solar_capacity);
   else
      factor = 1;
   end
end
```

Listing 1: Controller Code

A.2 Diesel Generator Controlling Unit

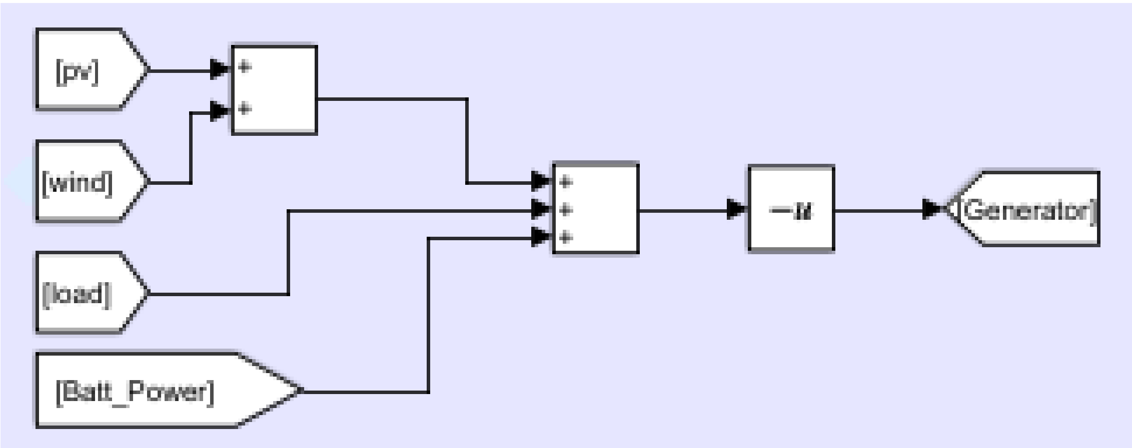

Figure 17: Diesel Generator Controlling Unit

A.3 Wind Turbines

The wind turbines were selected from a wind turbine marketplace. From here the new wind turbines with a rated power between 0 and 120kW were chosen. This mainly had to do with the fact that only a steady energy supply of 90kW needs to be supplied to the 160 households, as described in the Data Analysis section.

To determine which wind turbine will be used for the final design, a cost analysis and life cycle analysis were conducted. Finally, the results were put into a Harris Profile to determine the final decision.

A.3.1 Cost Analysis

To conduct the cost analysis, an assumption has to be made of a situation where the power generated to comply to the load, is solemnly done by wind turbines. The average wind speed is taken from the Data Analysis section and the power that needs to be generated is 90kW. The other parameters given are shown in the figure below.

	Prated [W]	v_rated [m/s]	v_average [m/s]	Load [W]	Costs per turbine
Fuhrländer FL 30	30000	12	6.45	90000	€ 12,000.00
Enercon E-18	80000	12	6.45	90000	€ 30,000.00
Ventis V20 100	100000	13	6.45	90000	€ 95,000.00
Tacke TW 60	60000	12	6.45	90000	€ 40,000.00

Figure 18: Parameters given for the wind turbines

First the power generated by one turbine for each type of turbine is calculated by:

$$\text{P\_turbine} = \text{P\_rated} * (\text{v\_average}/\text{v\_rated})^3 \tag{1}$$

Then the amount of turbines needed is calculated by:

$$\text{number of turbines} = \text{P\_load}/\text{P\_turbine} \tag{2}$$

Finally, the total costs are calculated by:

$$\text{total costs} = \text{costs per turbine} * \text{number of turbines} \tag{3}$$

The results are listed in the table below.

	P_turbine [W]	Turbines needed	Total costs
Fuhrländer FL 30	4658.613281	20	€ 240,000.00
Enercon E-18	12422.96875	7	€ 210,000.00
Ventis V20 100	12213.75171	7	€ 665,000.00
Tacke TW 60	9317.226563	9	€ 360,000.00

Figure 19: Calculation results

A.3.2 Life Cycle Analysis (LCA)

Life Cycle Analysis (LCA) is a method used to assess the environmental impact of a product across its whole life cycle. The LCA was conducted using the Idemat2017 database [3] in combination with the information given from the wind turbines (Figure 20, 21, 22 and 23).

The LCA consists of four parts: manufacturing, use, transport and end of life. In these LCAs transport was left blank, since there was no information about the transportation of each wind turbine.

Manufacturing		Eco-intensity (impacts/kg)	Mass per item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	Glass Fiber (material)	0.41	1100.000	1.00	10%	Rotor + 2 Blades	451
	Cast Steel (material)	4.14	3600.000	1.00	100%	Nacelle	14904
	Steel (material)	1.62	19200.000	1.00	30%	Tower	31104
	Paint corrosion coating	1.03	19200.000	1.00	100%	Tower	19681.877
							0
							0
Use		**Eco-Intensity (impacts/kWh or other)**	**Amount per item (kWh or other)**	**Items per func.unit (#)**	**Uncertainty %**	**Notes**	**Calculated Impact**
	Electricity, high voltage {CA-QC}| electricity produ	0.002528219	2139849300	1	10%		5410008.1
							0
							0
End of Life		**Eco-Intensity (impacts/kg)**	**Mass per item (kg)**	**Items per func.unit (#)**	**Uncertainty %**	**Notes**	**Calculated Impact**
	Steel recycling	-0.79	22800.000	1.00	100%	Tower + Nacelle	-18121.82
	Landfill (glass fiber)	0.00	20300.000	1.00	10%	Blades + Rotor	0
							0

Figure 20: LCA of the Ventis V20 100 wind turbine

Manufacturing		Eco-intensity (impacts/kg)	Mass per item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	Glass Fiber (material)	0.41	1900.000	1.00	10%	Rotor + 3 Blades	779
	Cast Steel (material)	4.14	5000.000	1.00	100%	Nacelle	20700
	Steel (material 50%)	1.62	19000.000	1.00	30%	Tower	30780
	Concrete (material 50%)	261.26	19000.000	1.00	30%	Tower	4963877
	Paint corrosion coating	1.03	19000.000	1.00	100%	Tower	19476.86
							0
							0
Use		**Eco-Intensity (impacts/kWh or other)**	**Amount per item (kWh or other)**	**Items per func.unit (#)**	**Uncertainty %**	**Notes**	**Calculated Impact**
	Electricity, high voltage {CA-QC}| electricity prod	0.002528219	2176504125	1	10%		5502679
							0
							0
End of Life		**Eco-Intensity (impacts/kg)**	**Mass per item (kg)**	**Items per func.unit (#)**	**Uncertainty %**	**Notes**	**Calculated Impact**
	Steel recycling	-0.79	24000.000	1.00	100%	Tower + Nacelle	-19075.6
	Landfill (glass fiber, concrete, paint)	0.00	39900.000	1.00	10%	Blades + Rotor	0
							0

Figure 21: LCA of the Enercon E-18 wind turbine

Manufacturing		Eco-intensity (impacts/kg)	Mass per item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
	Glass Fiber (material 50%)	0.41	800.000	1.00	10%	Rotor + 3 Blades	328
	Carbon Fiber (material 50%)	10.82	800.000	1.00	10%	Rotor + 3 Blades	8656
	Cast Steel (material)	4.14	1000.000	1.00	100%	Nacelle	4140
	Steel (material)	1.62	3000.000	1.00	50%	Tower	4860
	Welding (process)	222.89	3000.000	1.00	50%	Tower	668670
							0
							0
Use		**Eco-Intensity (impacts/kWh or other)**	**Amount per item (kWh or other)**	**Items per func.unit (#)**	**Uncertainty %**	**Notes**	**Calculated Impact**
	Electricity, high voltage {CA-QC}| electricity produ	0.002528219	820919446.8	1	10%		2075464.3
							0
							0
End of Life		**Eco-Intensity (impacts/kg)**	**Mass per item (kg)**	**Items per func.unit (#)**	**Uncertainty %**	**Notes**	**Calculated Impact**
	Steel recycling	-0.79	40000.000	1.00	100%	Tower + Nacelle	-31792.67
	Landfill (carbon fiber + glass fiber)	0.00	1600.000	1.00	10%	Blades + Rotor	0
							0

Figure 22: LCA of the Fuhrländer FL 30 wind turbine

In the manufacturing part, the material, coatings and manufacturing processes (e.g. welding) were taken into consideration. The eco-intensity was looked up in the Idemat database and the mass of the different parts of the wind turbines were found in the each corresponding datasheet. The uncertainty was determined by to what extend a perfect database match was found, where 10% corresponds with a perfect match and 100% corresponds with a wild guess.

Manufacturing	Eco-intensity (impacts/kg)	Mass per item (kg)	Items per func.unit (#)	Uncertainty %	Notes	Calculated Impact
Glass Fiber (material)	0.41	1400.000	1.00	100%	Rotor + 3 Blades	574
Cast Steel (material)	4.14	3600.000	1.00	100%	Nacelle	14904
Steel (material)	1.62	13000.000	1.00	100%	Tower	21060
Paint corrosion coating	1.03	13000.000	1.00	100%	Tower	13326.271
						0
						0
Use	**Eco-Intensity (impacts/kWh or other)**	**Amount per item (kWh or other)**	**Items per func.unit (#)**	**Uncertainty %**	**Notes**	**Calculated Impact**
Electricity, high voltage {CA-QC}| electricity produ	0.002528219	1632378088	1	10%		4127009.6
						0
						0
End of Life	**Eco-Intensity (impacts/kg)**	**Mass per item (kg)**	**Items per func.unit (#)**	**Uncertainty %**	**Notes**	**Calculated Impact**
Steel recycling	-0.79	16600.000	1.00	100%	Tower + Nacelle	-13193.96
Landfill (glass fiber + paint)	0.00	14400.000	1.00	10%	Blades + Rotor	0
						0

Figure 23: LCA of the Tacke TW 60 wind turbine

In the use part, the eco-intensity over the energy production of one turbine was estimated. The amount per item was determined by the following formula:

amount per item = power generated by one turbine [W] * 24 [hr/day] * 365[days/year] * lifetime

The lifetime was assumed to be 20 years.[9]

At some point the wind turbines will wear out over time. In the end of life part, the process of what happens with the last bit of the material will be taken into account (e.g. recycling, combustion, landfills). Only steel recycling and the material ending up in landfill were taken into account.[9]

A visualization of the LCAs of all the turbines are given in Figure 24.

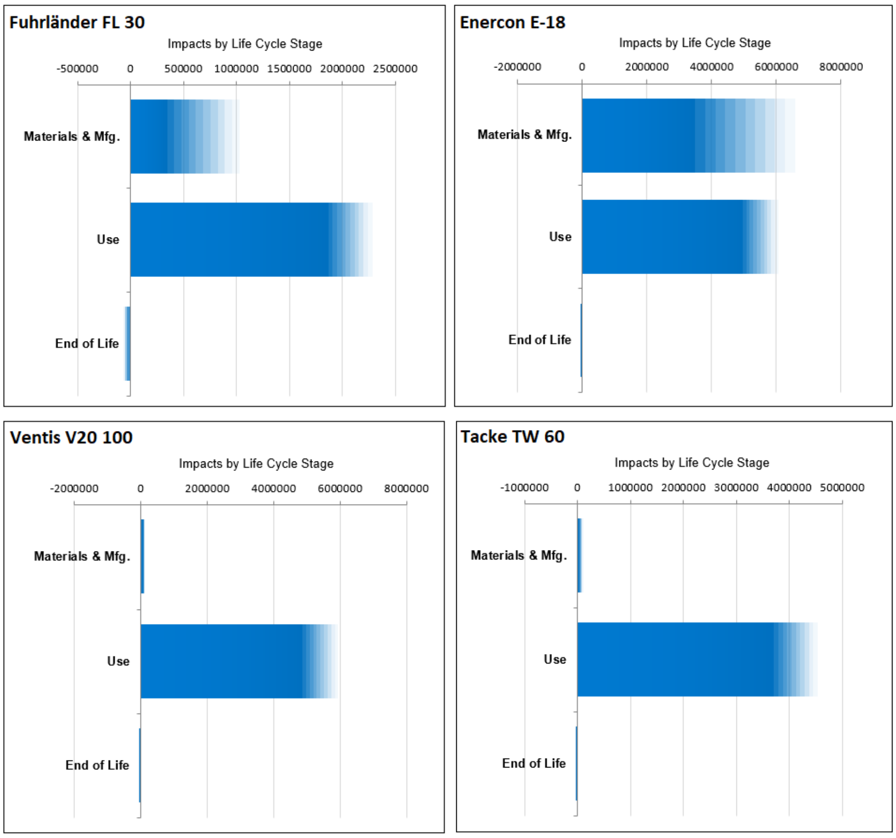

Figure 24: Visual representation of all the LCAs of all the wind turbines

A.3.3 Harris Profile

A Harris Profile is a method used in the Delft Design Guide, in which a visualization is made of the strengths and weaknesses of various options in a design concept[2]. First a list of requirements should be established and ranked in order from most important to least important. Then a matrix is formed with a scale of -2, -1, +1, +2. Each design option is then rated based on how well they solve each requirement. If they do it to a certain extent then they are graded with a +1. If it fails but by a small margin then they are graded by a -1. If they perform well by the requirements, then they are graded by +2. If they do not meet the requirement at all, they are graded with a -2. In the end multiple are formed that literally tends to lean either the positive side or the negative side. The matrix that leans to most towards the positive side will comply to the criteria the most.

The criteria on which the Harris Profiles will be evaluated from most important to least important is: costs, sustainability and area. This information is collected from the previous analyses.

As can be seen in Figure 25 , the Fuhrländer FL 30 has the tendency to lean the most towards the positive side in comparison to the rest of the wind turbines. Therefore this wind turbine is choosen for the final microgrid design.

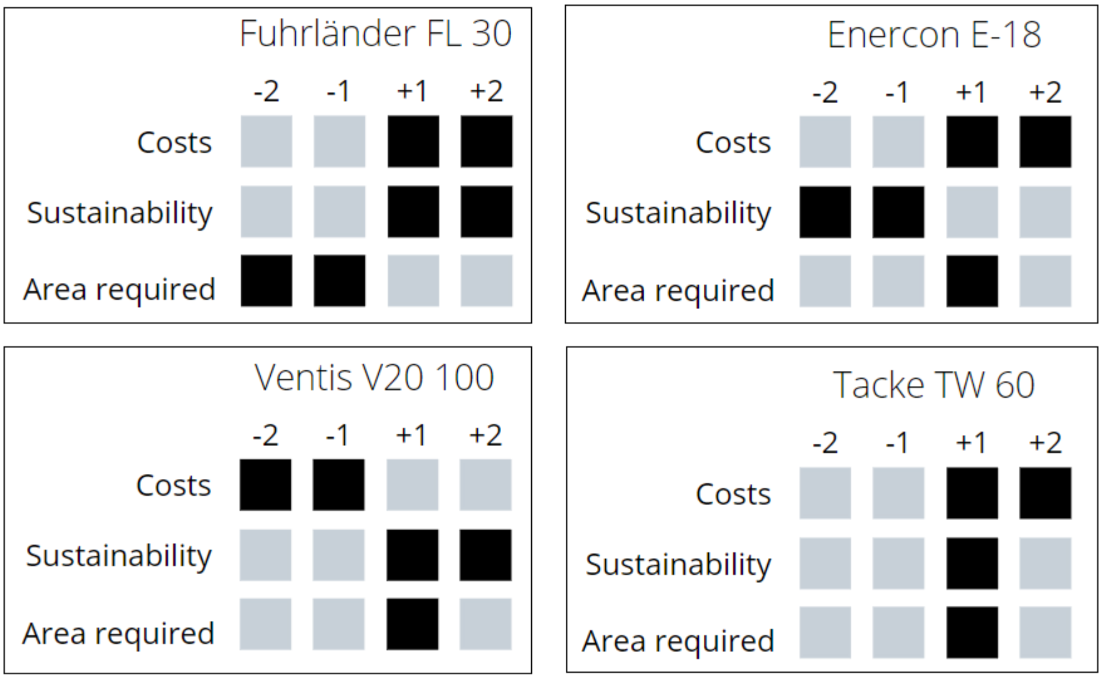

Figure 25: Harris Profile of the four chosen wind turbines

A.4 Solar Panels

The decision of the solar panels was also determined by means of a Harris Profile. However the order of importance for the criteria is different since solar panels are already very sustainable. The criteria for the solar panels were the costs, the amount of solar panels needed and the area that they take up. First a cost analysis was conducted, then the results of the cost analysis was implemented in Harris Profiles and afterwards the result of the Harris Profile concluded in a solar panel that should be used in the final microgrid design.

A.4.1 Cost analysis

For the cost analysis, a situation was assumed where:

- A load of 90kW needs to be supplied to the 160 households
- The average irradiance is based on the historical data of 2013-2015, which is 0.22kW/m2
- An average efficiency is assumed of approximately 20%

First, the area of the solar panels needed to comply to the 90kW should be determined by:

$$A\_needed = P\_load/(Irradiance\_average/\eta) \tag{4}$$

Then the area per solar panel should be determined by:

$$A\_panel = Length\_panel/Width\_panel \tag{5}$$

Now the amount of solar panels are determined by:

$$\text{number of solar panels} = A\_needed/A\_panel \tag{6}$$

Finally the total costs are calculated by:

$$\text{total costs} = \text{costs per solar panel} * \text{number of solar panels} \tag{7}$$

The results are listed in the table below.

	Load [W]	Area per solar panel (m2)	Solar panels needed	Price per solar panel	Total costs
LONGI SOLAR LR4355	90000	1.82169	1123	€ 139.00	€ 156,073.86
JA SOLAR 365WP	90000	1.868352	1095	€ 145.00	€ 158,744.66
LONGI SOLAR LR 365 WP	90000	1.868352	1095	€ 154.00	€ 168,597.78
JINKO SOLAR 355WP	90000	1.741068	1175	€ 155.00	€ 182,098.26

Figure 26: Tabel of the parameters given and results of the cost analysis

A.4.2 Harris Profile

The cost analysis results and the information given in the data sheets of the solar panels resulted in the Harris Profiles below. This figure shows that the JA SOLAR 365WP seems to be the best choice for the final microgrid design.

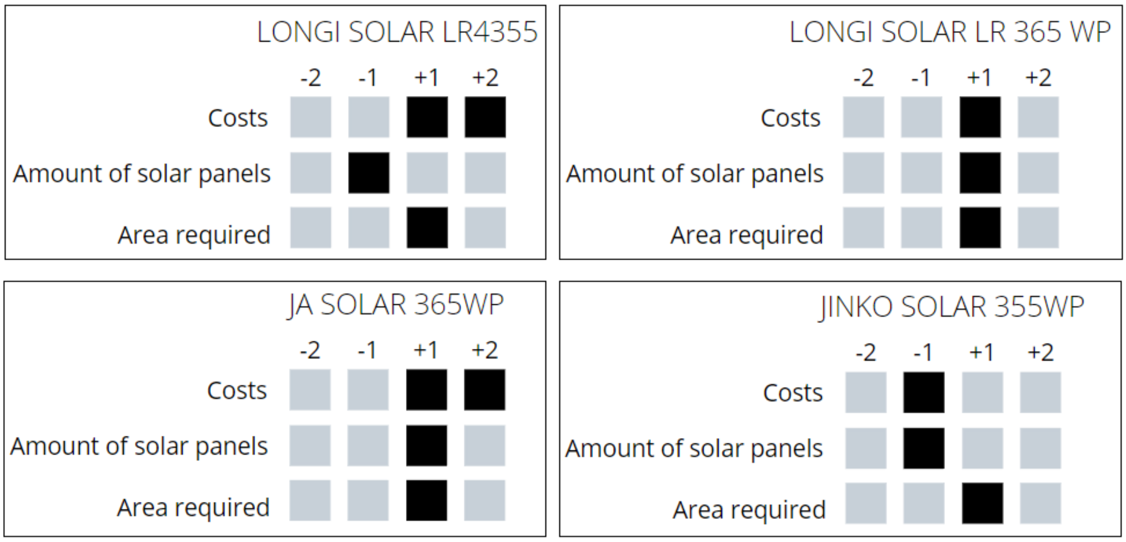

Figure 27: Harris Profile of the four chosen solar panels

A.5 Energy supply/demand

Figure 28: The supply/demand of energy in the year 2013 for an islanded model

Figure 28 shows how the energy demand/supply looks with the configuration of 30/70 (Solar/Wind) for the year 2013 for an islanded model.

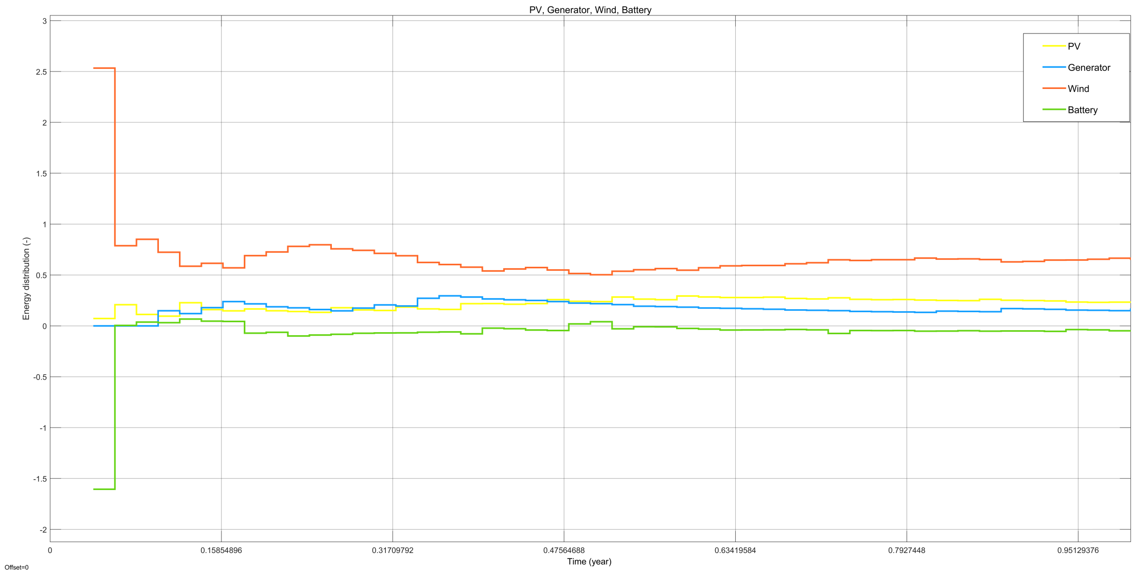

Figure 29: The energy distribution for an islanded model in the year 2013.

This figure 29 reveals how the distribution of energy is being read with a combination of 30/70 solar/wind energy. The final point of the graph is the total distribution for a whole year.

6.6 Test Data Analysis

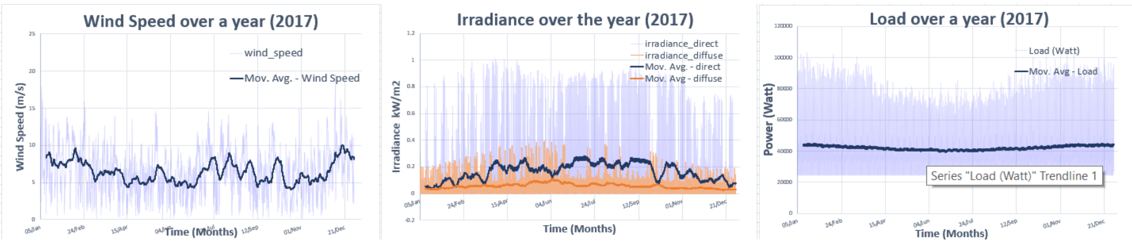

Figure 30: Dataset visualisation for the year 2017

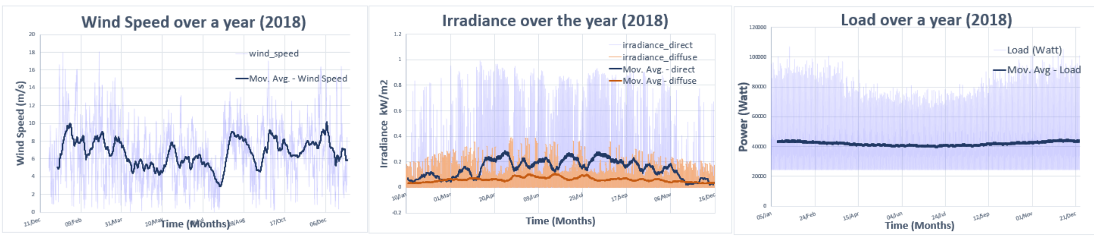

Figure 31: Dataset visualisation for the year 2018