Technoeconomic Study of Electric Vehicles (EVs) Charging

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***Abstract*—The gradual adoption of Electric Vehicles (EVs) sees microgrids struggling to adapt to the new load as the market races to prove the economic feasibility of the technology. More infrastructure is required to bolster the transition to this cleaner form of transport, but the market faces uncertainty in this new and developing industry as there are limited data and tools. This project involves designing a technoeconomic model of EV charging, packaged as a python software and complete with Graphical User Interface (GUI). The model is heavily inspired by a previous study done by J.J. Yeoh which involved modelling a technoeconomic assessment of EV charging strategies. It aims to find the appropriate values to price the EV charging services as well as the optimal strategies to maximise revenue. The purpose of the software is to help charging service operators to make informed decisions and provide a smoother onboarding of EVs infrastructure providers into the current economy.**

***Index Terms*— Electric Vehicles, charging, technoeconomic, energy storage systems**

I. Introduction

In the recent years, societies are starting to recognise and acknowledge current environmental issues such as climate change [1] the global energy crisis [2]. As societies transition to cleaner forms of energy, new technological revolutions such as microgrids and EVs are introduced. Microgrids serve as a more resilient, robust and effective method of incorporating renewable energy into electrical grids [3], whereas EVs produce lesser pollutants then their internal combustion engine (ICE) counterparts [4].

In 2021, transportation alone accounts for 28% of the total energy usage in the United States [5], highlighting the promising benefits of EVs. A study performed by Ferroro et al. estimated that replacement of half the light vehicles would decrease NO_2 and NO_x concentration in the area by 5.5% and 14.1% [6]. In Denver, U.S., the replacement of all on-road mobile sources of pollutants with plug-in hybrid EVs (PHEVs) would reduce NO_x their emissions by 16% (equivalent of 27 tons per day) with a trade-off with a 2% increase in NO_x from power plants which is approximately equivalent to 3 tons per day [7]. Jacobson et al. estimated that EVs powered by renewable energy could save 3700 to 6400 lives annually [8] whereas another study conducted by Tessum et al. estimated that adverse health impacts could be reduced by 50% through the replacement of ICE vehicles with EVs powered by renewable energy [9].

However, the advent of EVs see microgrids struggle to adapt to the new demand [10]. The lack of accurate EV charging models contributes to the challenge of EV integration into the market as businesses are unable to accurately assess the risk involved as well as the optimal strategies to employ [11].

A. Microgrids

According to the U.S. Department of Energy, a microgrid is a group of interconnected loads and distributed energy resources (DER) within distinct electrical boundaries, acting as a single control entity that can connect or disconnect from the main grid [12]. This study is concerned with solar microgrids with EV charging loads and the following are the components of a solar microgrid instrumental to this project [13]:

1. Solar Photovoltaics (PVs)
2. Energy Storage System (ESS)
3. Inverters
4. Converters (for conversion to DC Loads)

Solar PVs are semiconductors that convert incident light radiation from the sun into electrical energy [14]. However, irregular solar irradiance due to the natural movement of the sun causes irregular power output [15] [16]. As such, ESS is typically integrated into the microgrid to even out peak loads [16].

Moreover, as the grid is commonly using Alternating Current (AC) power, but power output from the solar PVs is Direct Current (DC), hence, inverters are introduced to the system to convert the DC output from the solar PVs to useable AC in the grid [17].

Additionally, EV chargers operate in DC and hence, converters are required to convert the AC power from the grid to DC power output [18]. Converters can be installed onboard the EV itself or on the grid side [18].

B. Yinson Green Technology (YGT)

This project is done in collaboration with YGT; it is the green technologies division of Malaysia-based Yinson Holdings Berhad listed on Malaysia's stock exchange [19]. Headquartered in Singapore, it aims to provide a clean, integrated and technological ecosystem in different industries including marine, mobility, energy and digital sectors [20]. Currently, it operates an EV charging station at Ayer Keroh's Rest & Relaxation (R&R) facility along Malaysia's North-South highway.

II. Scope and Objectives

The main purpose of the project is to design and create a python software with a GUI that allows user interaction with a technoeconomic model backend. The model is heavily inspired by a previous study done by J.J. Yeoh where a 5-year technoeconomic analysis is conducted on the Ayer Keroh's R&R facility operated by Yinson [21].

A. *Analysis of different EV charging prices*

An objective of the model involves finding the required EV charging price to charge for the business to breakeven in that year. Additionally, the model should also be able to observe the different revenue for the different price levels.

B. *Optimal ESS strategies*

The model should also be able to determine the optimal ESS sizing according to the different parameters. Furthermore, it should be able to compare between the 2 ESS charging strategies indicated in Yeoh's study [21].

C. *Scenario analysis of different demand*

The model should be able to observe the changes in technical and financial parameters according to the different demand levels.

D. *Charging Station Availability*

The model will predict the availability of the EV charging station according to the demand.

III. LITERATURE REVIEW

Yeoh's technoeconomic model also have similar objectives to this project and they are:

A. Finding optimal level of grid involvement in ESS charging strategies.
B. Predict availability of charging station according to demand.
C. Determine optimal energy storage system (ESS) sizing for an EV charging station, according to technical and financial parameters.
D. Scenario analysis for different demand and sensitivity analysis of minimum charging price to demand.

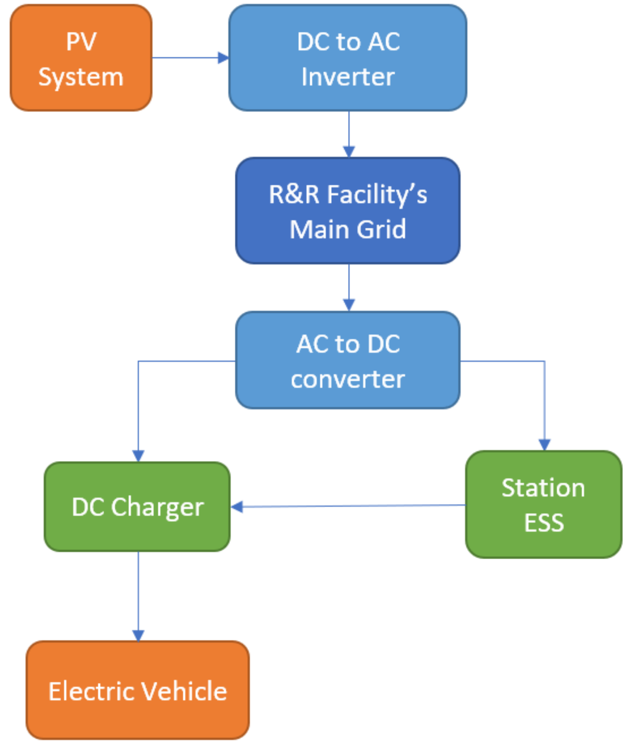


Fig. 1. Block diagram of the electrical flow of the Eyer Keroh EV charging site

Fig. 1 shows a block diagram of the electrical flow of the model. The PV system converts solar energy into useable DC electricity which is then converted into AC power output through the inverter to the R&R facility's main grid. The main grid then supplies electricity to both the ESS and DC charger through an AC to DC converter. The R&R facility's main grid also supplies electricity to other load that are not shown in the diagram as they are irrelevant in this study.

Yeoh's model is split into 3 sections [21]:

1. Solar Power Generation
2. Energy Storage System (ESS)
3. DC charging points

A. *Solar Power Generation*

According to values given by Yinson, the solar power generation capacity installed at the Ayer Keroh R&R is 27kWp [21]. The lower bound specific PV conditions is 3.58 kWh/hWp per day at the Melaka region and the boost inverter was assumed to be at 90% efficiency [21]. Thus, the average energy generated per day was calculated with this estimation:

$$P_{output} = P_{specific,PV} \times P_{capacity,PV} \quad (1)$$

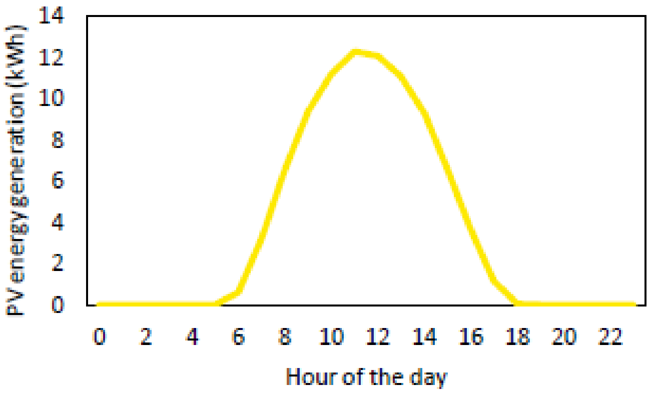


Fig. 2. Hourly profile of solar energy generation

Fig. 2 above shows the hourly solar generation profile of Ayer Keroh at coordinates 2.3982N, 102.2219E in 2019 [21].

B. ESS

Yeoh studied 2 different ESS charging strategies. Strategy 1 involves charging the ESS predominantly during off-peak hours and when the ESS reached its state of charge (SOC) limits during peak hours [21].

Equation (2) below calculates the energy stored in the ESS when it is charging from the grid whereas (3) calculates the energy stored in the ESS when it is discharging (i.e., charging EV).

$$E_{ESS,t} = E_{ESS,t-1} + E_{grid,t} \qquad (2)$$

$$E_{ESS,t} = E_{ESS,t-1} - E_{load,t} \qquad (3)$$

Where t represents the current hour, $E_{ESS,t}$ represents the energy stored in the ESS at time t, $ESS_{grid,t}$ is the energy drawn from the grid at time t and $E_{load,t}$ is the energy supplied from the ESS to the EV customer at time t.

Strategy 2 involves charging the ESS during off-peak hours and discharging of the energy stored in the ESS when the supply from the grid is insufficient during peak hours [21]. The energy stored in the ESS at time t, $E_{ESS,t}$ is calculated using (4) below:

$$E_{ESS,t} = E_{ESS,t-1} - \left(E_{peak,grid,t} - E_{load,t}\right) \qquad (4)$$

Where $E_{peak,grid,t}$ represents the energy supplied by the main grid during peak hour at time t.

C. DC Charger

According to the information provided by Yinson, the Ayer Keroh R&R is installed with a 180kW DC charger with two 90kW charging guns [21]. The battery capacity of the EV customers is assumed to be 54kWh with a 20% SOC at entry and 80% SOC on exit [21]. Hence, each customer is estimated to require 32.4 kWh in 1C charging [21].

D. Study Variables

The relationship between the daily number of EV charging station customers and charging price in RM/kWh are studied by Yeoh. In another research conducted by Chen, Functional Principal Component Analysis (FPCA) is performed to obtain the customer profile of EV charging is generated [22].

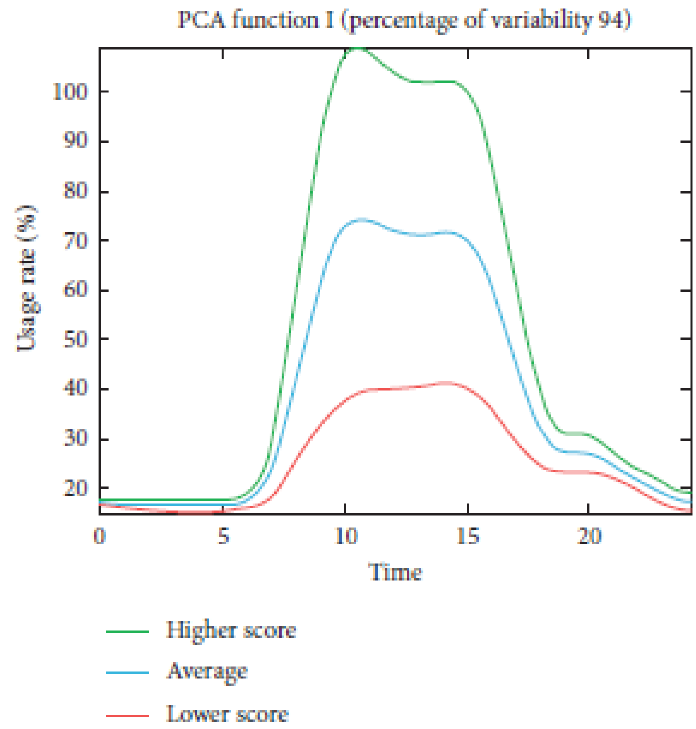


Fig. 3. FPCA results focusing on variability between 7A.M. and 5P.M. [22]

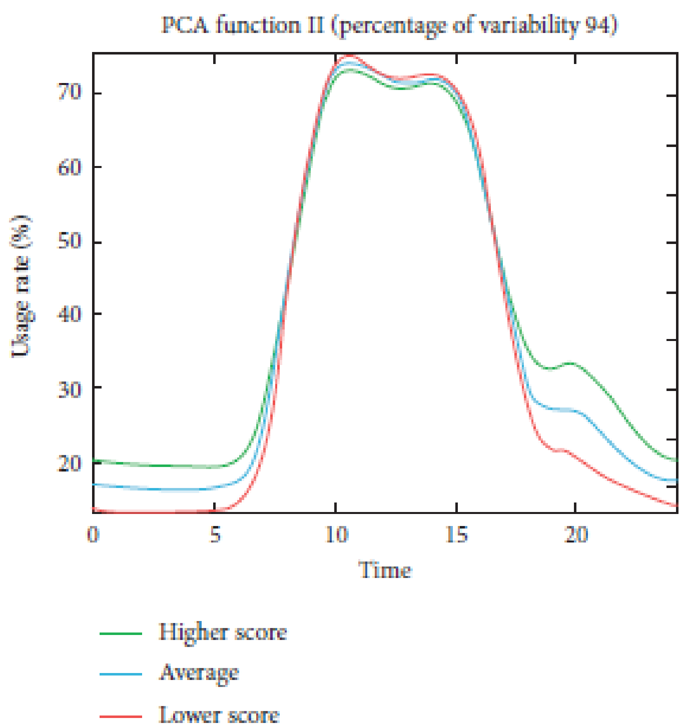


Fig. 4. FPCA results focusing on variability between 6P.M. to 6A.M. [22]

Fig. 3 and Fig. 4 captures the FPCA results for the EV charging usage performed by Chen. The blue curves represent the average occupancy of the charging stations involved in Chen's study, green curves represent the function after adding a functional component to the average curve and red curves represent the function after subtracting one functional component from the average curve [21]. Using Chen's results, Yeoh then assumed EV charging demand to start from 9A.M. in his study.

Yeoh also varied the EV charging price to determine the minimum breakeven for the different levels of demand [21].

E. Economic Analysis

The internal rate of return (IRR) over a five-year lifetime was evaluated using (5) below:

$$NPV = 0 = CF_0 + \sum_{t}^{N} \frac{CF_t}{(1 + IRR)^t} \qquad (5)$$

N: $project\ lifetime\ in\ years$
t: $current\ year$
CF_0: $initial\ capital\ expenditure$
CF_t: $annual\ cash\ flow\ for\ the\ year\ t$

CF_t in (5) is calculated using the operating cash flow whose formula is given in (6) below:

$$OCF_t = NI_t + Depre_t \qquad (6)$$

Where $Depr_t$ represents the total EV charger and ESS depreciation and NI_t represents the net income for the year t that is obtained using (7) below:

$$NI_t = (R_t - Opex_t - Depr_t) \times (1 - tax) \qquad (7)$$

R_t: $the\ total\ revenue\ generated\ for\ the\ year\ t$
$Opex_t$: $total\ operating\ expenditure\ for\ year\ t$
tax: $corporate\ tax\ rate$

For tax, the corporate tax rate in Malaysia is used in Yeoh's study. R_t is calculated from the following equation:

$$R_t = R_{charger} + R_{facility} \qquad (8)$$

Where $R_{charger}$ represents the revenue generated from the DC chargers themselves and $R_{facility}$ is the revenue generated from the sale of excess energy generated to the R&R facility.

$Opex_t$ is calculated from the following equation:

$$Opex_t = O\&M_{t,PV} + O\&M_{t,charger} + O\&M_{t,ESS} + Opex_{t,grid} \qquad (9)$$

$O\&M_t$: $operating\ and\ maintenance\ costs\ for\ the\ year\ t$
$O\&M_{t,PV}$: $O\&M_t\ of\ the\ solar\ PVs$
$O\&M_{t,charger}$: $O\&M_t\ of\ the\ DC\ chargers$
$O\&M_{t,ESS}$: $O\&M_t\ of\ the\ ESS$
$Opex_{t,grid}$: $Opex_t\ due\ to\ both\ peak\ and\ off-peak\ grid\ electricity\ costs$

$$R_{breakeven} = CF_0 + \sum_{t}^{N} Opex_t \qquad (10)$$

$$R_{charging} = R_{breakeven} - R_{facility} \qquad (11)$$

Equation (10) calculates the minimum revenue required to breakeven, $R_{breakeven}$, and (11) calculates the charging revenue required over the EV charging station lifetime, $R_{charging}$. Hence, the minimum charging price to breakeven is given as:

$$Price_{min} = \frac{R_{charging}}{N \times (Op_t \times 365) \times E_{day}} \qquad (12)$$

Where Op_t is the percentage of the year t that the station is operational. In Yeoh's study, this value is assumed to be 90% as given by Yinson. E_{day} is the actual energy supplied to the EV customers per day in kWh [21].

IV. METHODOLOGY

To create the real-time model in python, the QT 6 Framework is used with python bindings, packaged as a python package (pyside6) [23].

Model-View-Controller (MVC) software design pattern is observed where model represents the underlying data, view is responsible for the GUI display and the controller act as a coordinator between the model and the controller [24]. In this python program, the model are the actual values of the parameters and are python files stored in the model directory. The view related codes are stored in a separate directory and is responsible for the user interface as shown in the figures in the results section. The controller is the codes that listens for a user event such as a button click or a key press and the equations governing the relationships between each parameter.

The technoeconomic model is split into 4 different sections:

1. Hourly Solar Power Generation
2. Hourly Charging Demand
3. Technical
4. Financial

A. Hourly Solar Power Generation

Hourly solar power generation is responsible for the hourly solar energy generation profile. Using the daily solar generation value of 86.99 kWh estimated by Yeoh [21], and the hourly solar irradiance profile at the Ayer Keroh site, the hourly profile for the solar energy generation is generated. Daily values are obtained from the technical section.

B. Hourly Charging Demand

Hourly charging demand allows user to set the daily number of customers. An hourly profile of the EV charging users is then generated using the EV customers profile in Chen's study, filling up the peak hours first.

C. Technical

The technical section itself is comprised of 3 sections:

1. Solar power generation which allows the user to set the installed capacity of the solar power generation, the Ayer Keroh site solar daily conditions and boost inverter efficiency, thus obtaining the estimated daily energy output.
2. Charging and demand which is responsible for the charging specifications such as the power rating and the

number of chargers. This subsection also allows the changing of the EV characteristics to estimate the load required per customer.

3. Battery storage where ESS specifications are adjusted such as the installed capacity, depth of discharge (DoD), nameplate lifecycle. Discharge power and the electricity required from the grid are also contained in this subsection. Most importantly, the ESS charging strategies suggested by Yeoh are implemented in this section.

D. Financial

The financial section also involves 3 subsections:

1. Capital expenditure which includes the prices of the facilities in the technical section and their depreciation costs.
2. Operating expenditure which involves the operational and maintenance (O&M) costs.
3. Revenue where the tariff assumptions can be set and thus, showing the revenue required to breakeven and thus the EV charging price to pass on to the consumers.

V. RESULTS

This section presents the stable version of the python program. As many of the yearly values were obtained through their corresponding daily values, every year is assumed to have 365 days, and hence, the yearly values are obtained by multiplying their corresponding daily values by 365. Parameters presented in this section were set to emulate the Ayer Keroh EV charging station as close as possible.

A. Hourly Solar Power Generation

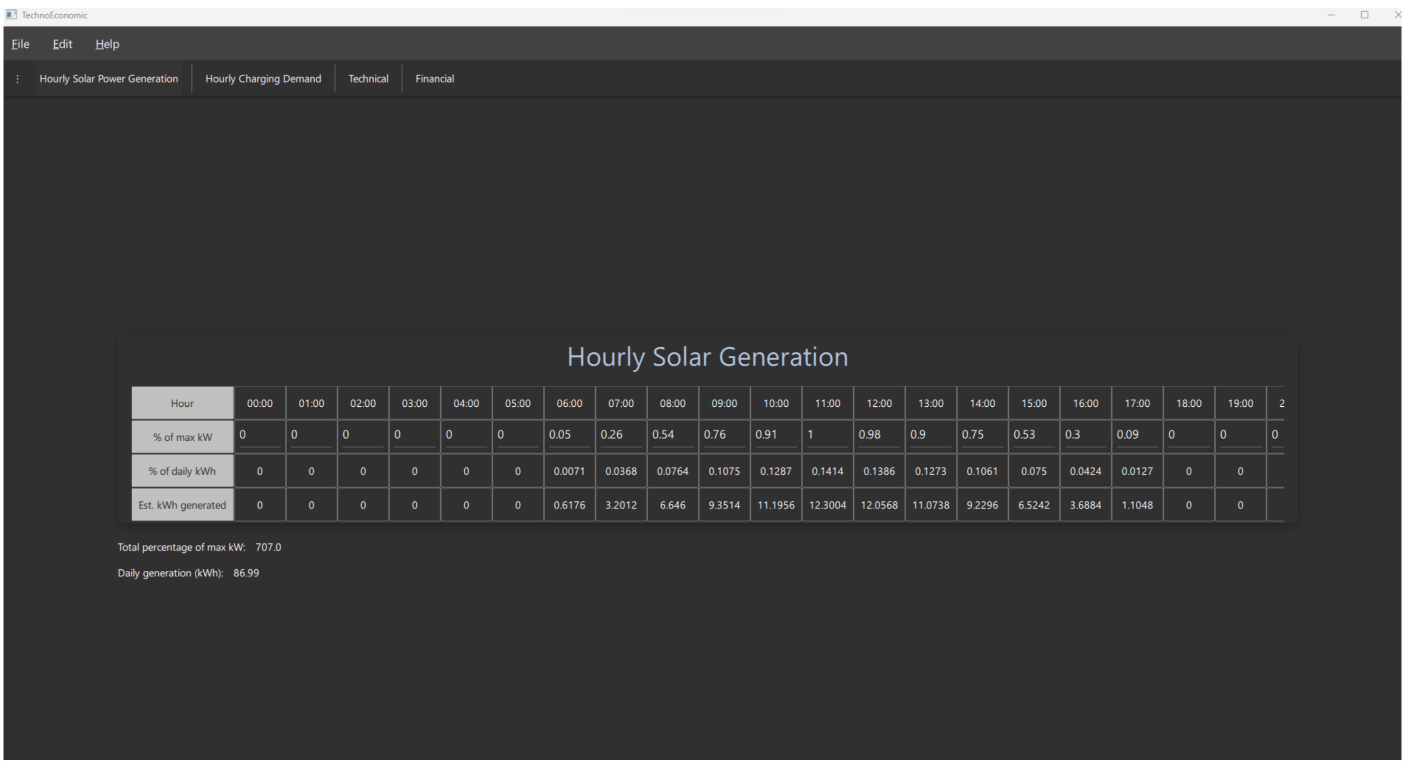


Fig. 5. Hourly solar generation section of python program

Fig. 5 shows the hourly solar generation section of the python program, where there is a row to set the hourly profile of the solar generation. An important error to be aware of in this section is that the percentages currently represent actual raw values rather than the number of percent. The values in the figure above are set in accordance with the solar profile referenced in Yeoh's research. Total percentage of maximum kilowatts (kW) is obtained by the summation of the values in the estimated kW-hour (kWh) generated row. Daily solar generation value is obtained from the technical section.

B. Hourly Charging Demand

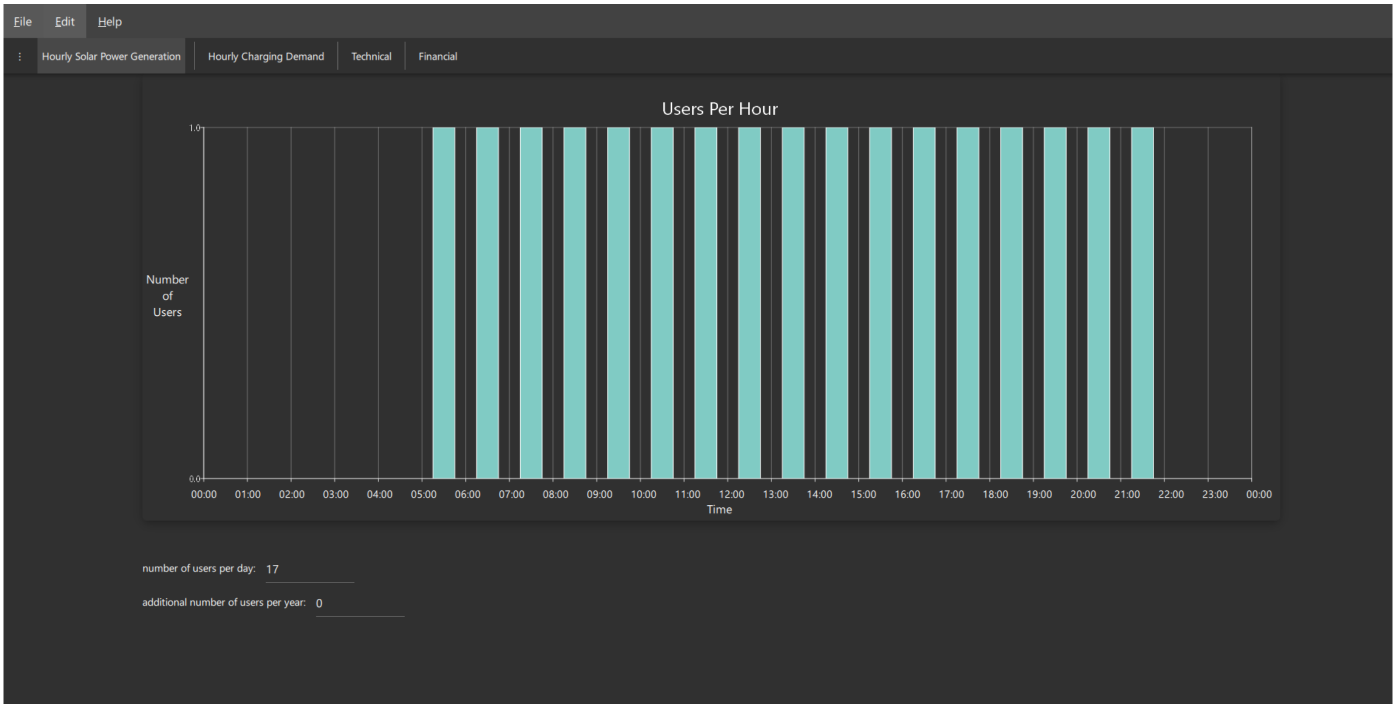


Fig. 6. Hourly charging demand section of the python program

Fig. 6 shows the EV charging customer profile, prioritising the peak hours first followed by the non-peak hours as indicated by Chen's study on EV charging behavioural pattern. Additional number of users per year allow the user to adjust this parameter for a five-year analysis as mentioned by Yeoh. However, in this version, the five-year analysis is incomplete.

C. Technical

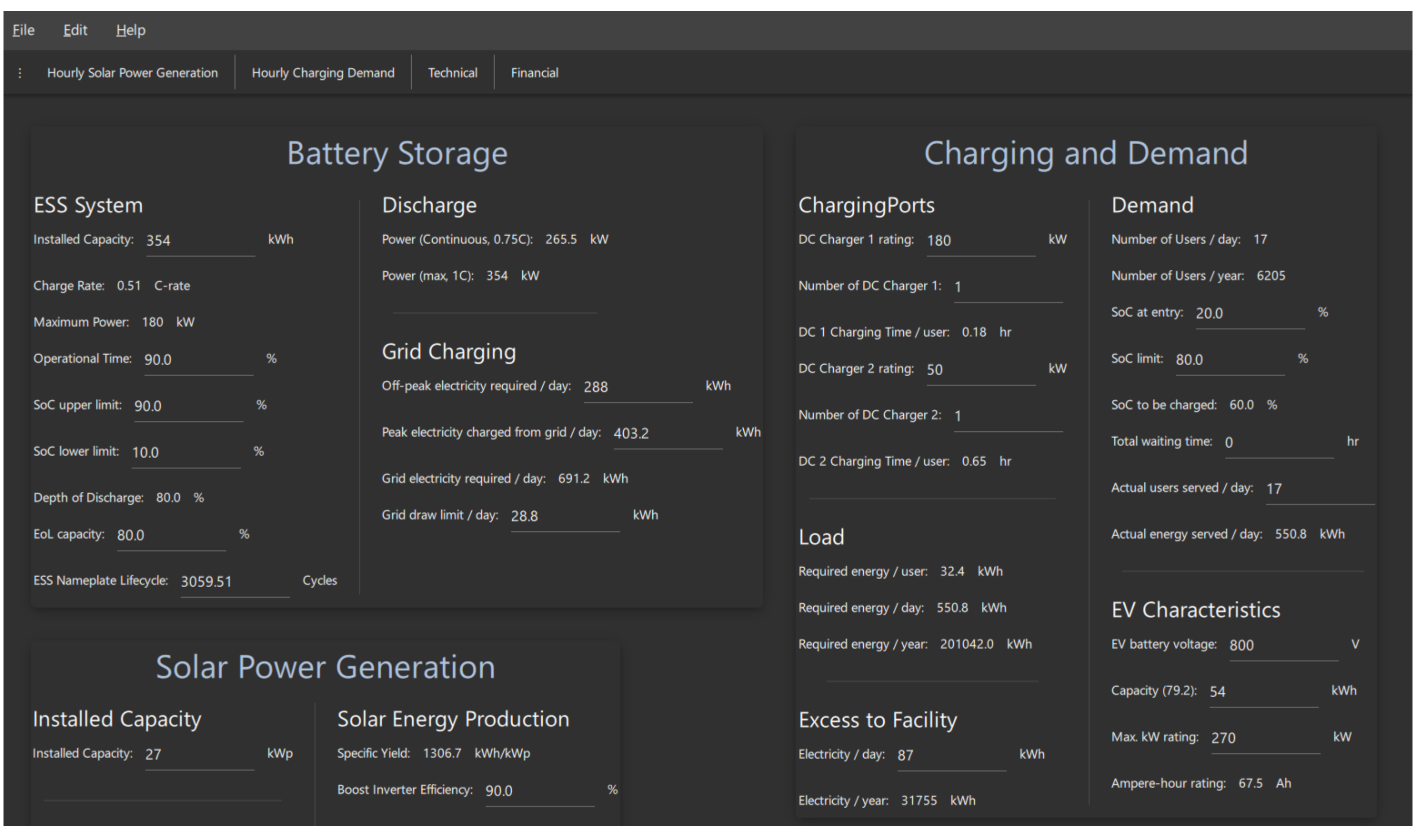


Fig. 7. Technical section of the python program

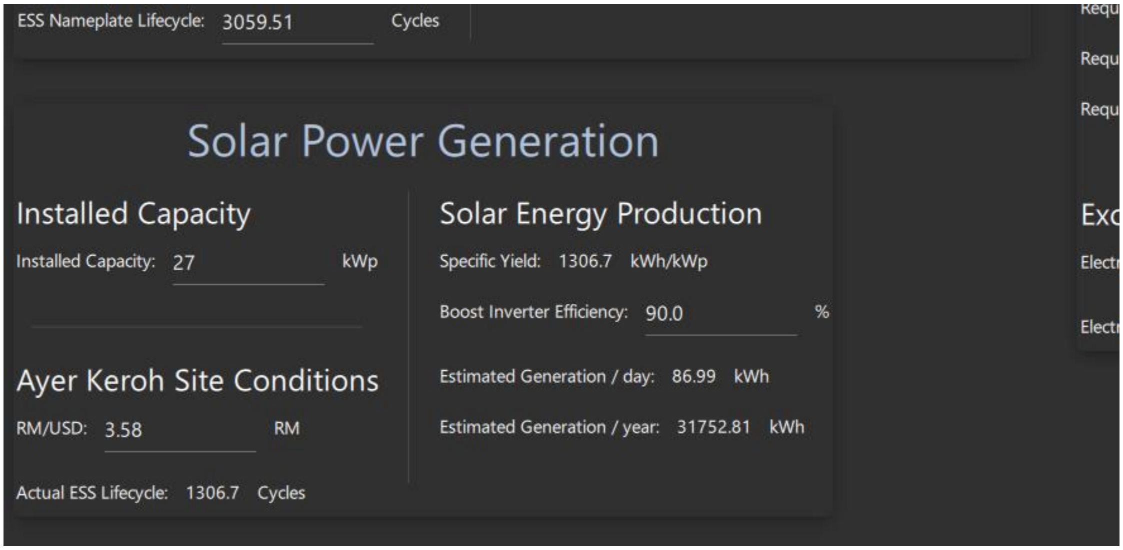


Fig. 8. Full view of the solar power generation subsection of the technical section

Fig. 7 shows the 3 subsections of the technical section. Unlike the percentages in the hourly solar power generation, percentages are represented correctly in this section. Parameters adjustable by the user can be distinguished by the input text fields with an underline. The input values shown in the figures above are those provided by Yinson and Yeoh's study.

As the technical section is too large to be rendered in a single page, the section is encapsulated in a scroll view. Fig. 8 shows the full view of the solar power generation subsection after the view is scrolled further downwards.

D. *Financial*

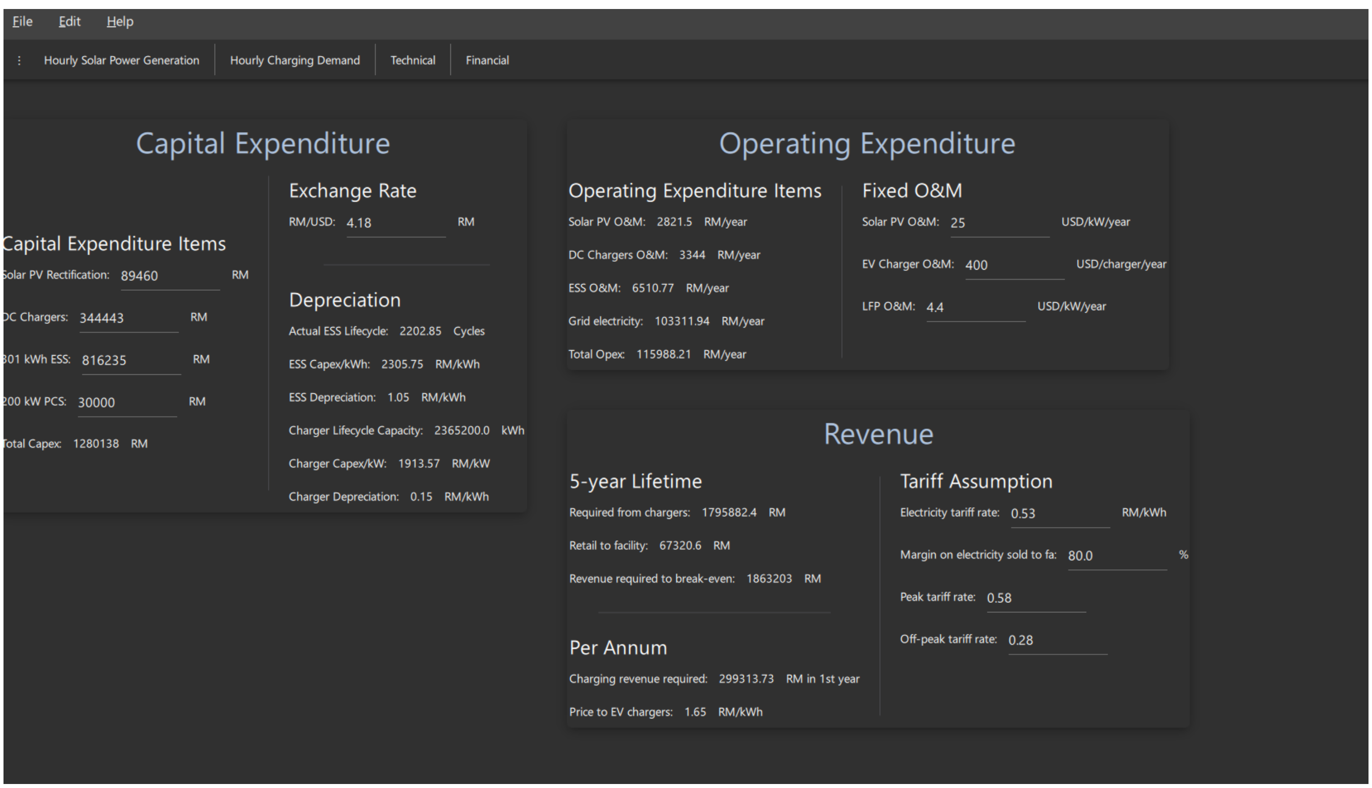


Fig. 9. Financial section of the python program

Figures 5 shows the financial section and the values in the figure are also provided by Yinson. Using the parameter values of the Ayer Keroh R&R facility provided by Yinson, the model estimated the minimum price required to breakeven, $Price_{min}$ to be 1.65 R.M.

VI. CONCLUSION

The python program presented in the results section is a stable version but with limited features. The current model at the time of writing has vast improvements and better features than the model presented in the results section but is unstable and has incomplete features.

The results are constantly reviewed by Yinson; however, it is difficult to validate them as EV is still a new industry and thus, there are insufficient data. Despite this, technical values are verified with data provided by Yinson. The source code for the project is hosted publicly on GitHub, a remote repository hosting site [25].

A. Ongoing Work (Five-Years Analysis)

Yeoh proposed a five-years analysis to evaluate technical strategies. In this five-years analysis, the scenario customised by the user through the adjustments of the parameters is propagated for 5 years. Additional parameters such as the increase in the number of customers per year will be included to simulate the growing adoption of EV. Current efforts towards this five-year analysis are ongoing but is unstable and incomplete.

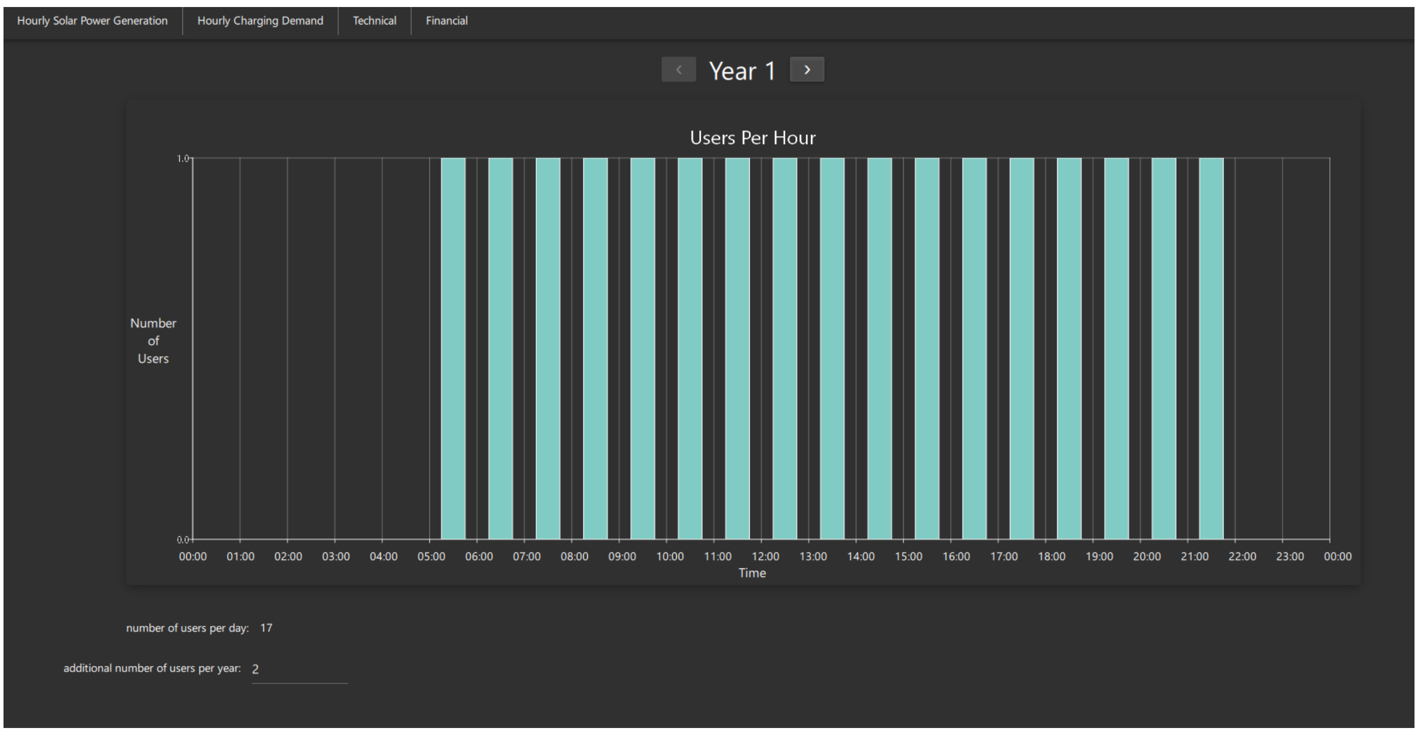


Fig. 10. Hourly charging demand for a day in the first year

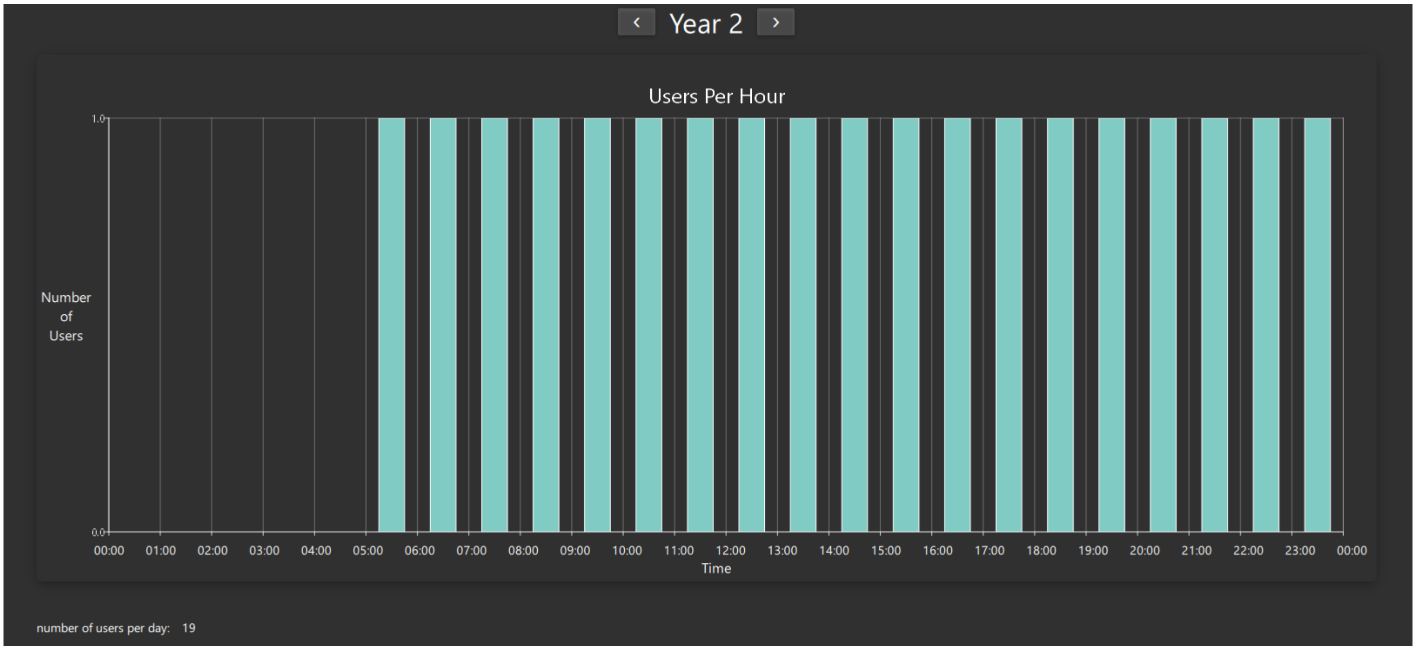
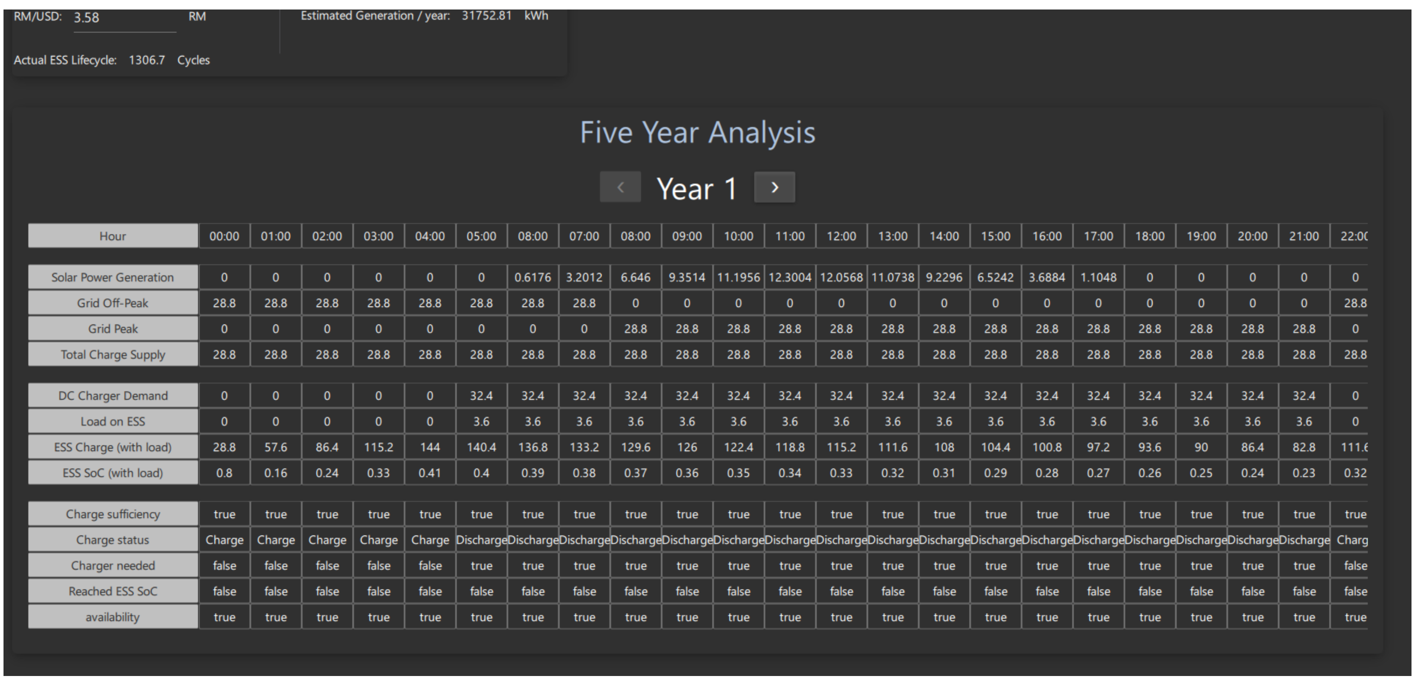


Fig. 11. Hourly charging demand in a day for the second year

Fig. 10 and Fig. 11 shows the five year analysis interface in the hourly charging demand section. In Fig. 10, it can be observed that the daily number of customers for the first year is 17. In Fig. 11, the daily number of customers for the second year is increased to 19 as the additional number of customers is set to 2 as observed in Fig. 10.



Hour	00:00	01:00	02:00	03:00	04:00	05:00	08:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:0
Solar Power Generation	0	0	0	0	0	0	0.6176	3.2012	6.646	9.3514	11.1956	12.3004	12.0568	11.0738	9.2296	6.5242	3.6884	1.1048	0	0	0	0	0
Grid Off-Peak	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28.8
Grid Peak	0	0	0	0	0	0	0	0	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	0
Total Charge Supply	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8	28.8
DC Charger Demand	0	0	0	0	0	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	0
Load on ESS	0	0	0	0	0	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	0
ESS Charge (with load)	28.8	57.6	86.4	115.2	144	140.4	136.8	133.2	129.6	126	122.4	118.8	115.2	111.6	108	104.4	100.8	97.2	93.6	90	86.4	82.8	111.6
ESS SoC (with load)	0.8	0.16	0.24	0.33	0.41	0.4	0.39	0.38	0.37	0.36	0.35	0.34	0.33	0.32	0.31	0.29	0.28	0.27	0.26	0.25	0.24	0.23	0.32
Charge sufficiency	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true
Charge status	Charge	Charge	Charge	Charge	Charge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Charg
Charger needed	false	false	false	false	false	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	false
Reached ESS SoC	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
availability	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true

Fig. 12. Hourly breakdown of the technical section in the first year of the five-years analysis

Figure 3 above shows an hourly breakdown in the technical section. This section allows the study of the EV charging station status which include the availability of the EV charging station. A year selector allows the user to view the hourly breakdown for the year selected.

B. Future Work: Vehicle-To-Grid (V2G)

V2G refers to the technology that allows EVs to serve as a power source for the electrical grid through bidirectional charging technology [26]. With this technology, EVs act as distributed mobile energy storages that can aid in peak-shaving and load-shifting [26].

However, V2G is still a developing technology that have uncertain outlook faces many adversaries such as increase battery degradation due to more discharge cycles [27] in addition to the extra capital and maintenance cost of the more complex bidirectional chargers themselves. Despite this, EV charging operators are attracted to this technology as most of the additional cost are absorbed by the consumers rather than the operators [28]. The drop in cost due to the decrease in ESS sizing required if V2G is more adopted might justify the efforts and costs for the service operators to integrate this technology. Hence, this python model will look to integrate V2G technoeconomic analysis and provide more insights into the feasibility of V2G

C. Schedule for 2^{nd} *Semester*

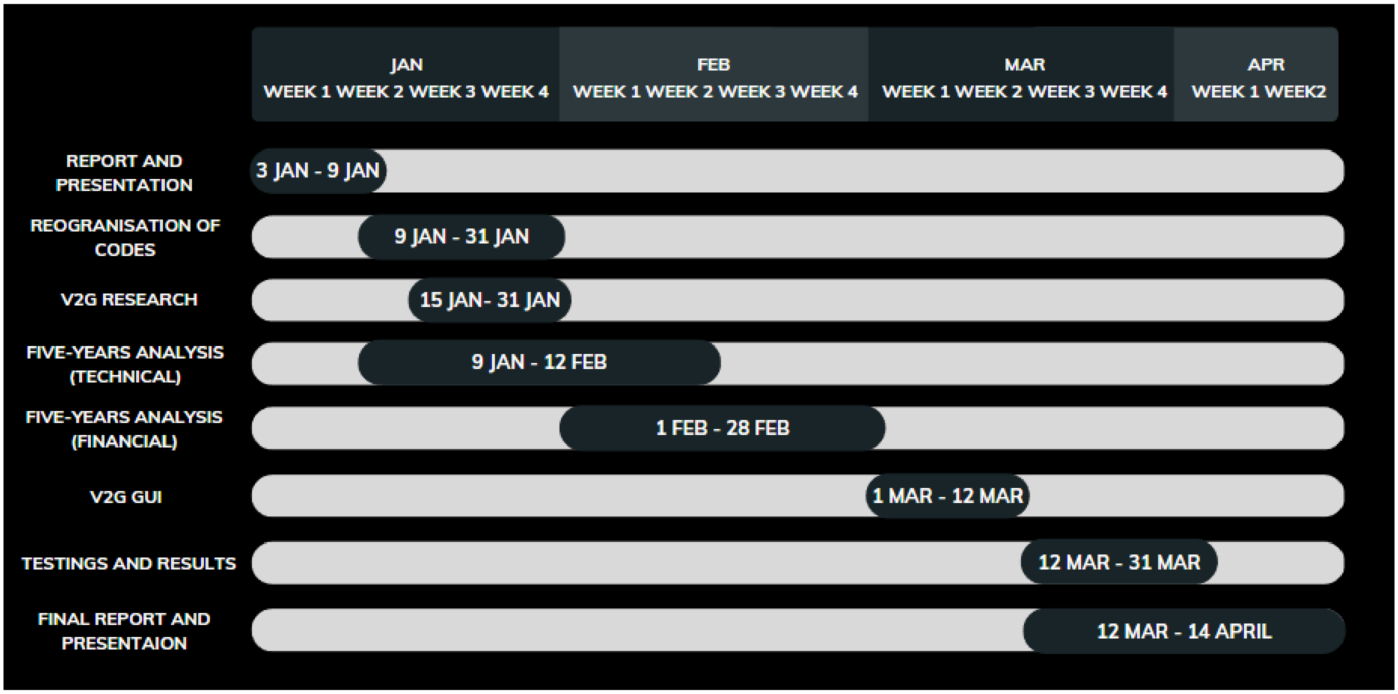


Fig. 13. Gantt Chart for the second semester

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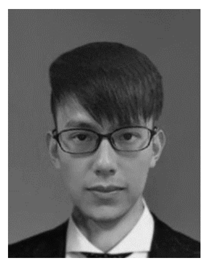

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