Project: Autonomous power systems for traffic lights in a city (Nancy)

Group Members:

- Anamta Farooque
- Adoos Khalid
- Omnia Abdulraheim
- Rajnesh Kumar

Problem Statement

The problem is to design a standalone system to provide power to traffic lights in Nancy, France using a combination of photovoltaic (PV) cells, a Li-ion battery, and a small PEM fuel cell. The system needs to operate throughout the year and meet the power demand of four traffic lights, each equipped with LED lamps with a total power demand of 60 W. The design should consider the power delivered by the sun throughout the year, the efficiency of the PV cells, the voltage and current of the fuel cell, the state of charge, voltage and efficiency of the battery, and the energy efficiency of the inverter. The system is shown in below figure:

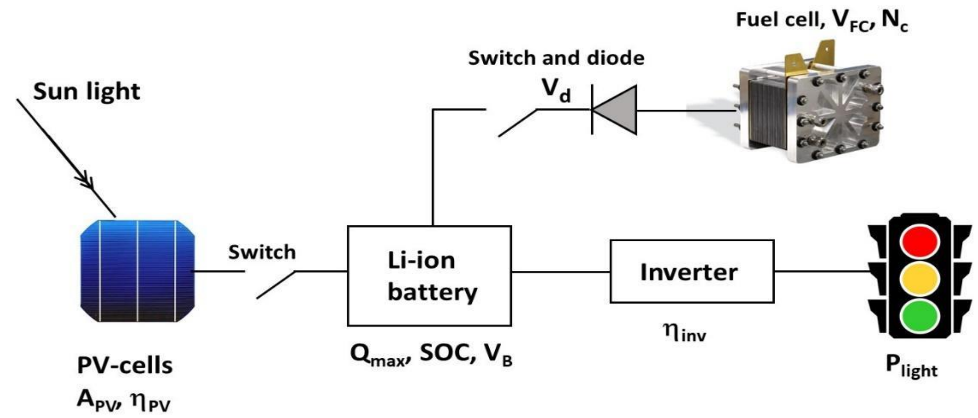


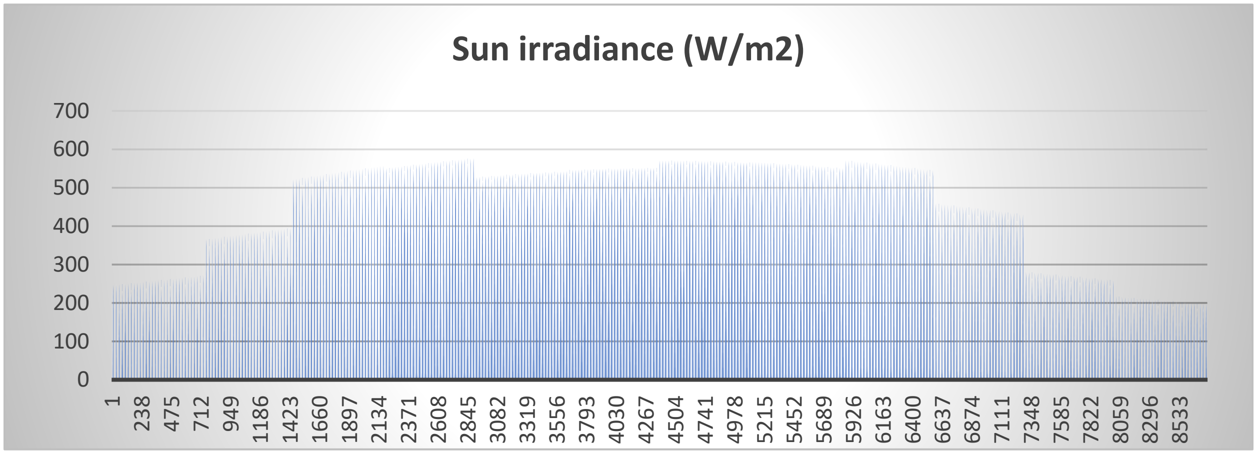
Figure 1: Schemed view of the standalone system to provide power to traffic lights

Data

The data provided below gives information about the power demand, solar power availability, PV cell efficiency, battery specifications, fuel cell specifications, and inverter efficiency. This data is necessary for designing and simulating the standalone system to power the traffic lights.

Solar Irradiation

1. The solar irradiance, S_{Irr}, data of Nancy for one year is provided as shown below:



Solar panel

2. The area of the PV cells, AP, is assumed to be **2 m²**.
3. The power efficiency of the PV cells, η_{PV}, is **20%** and independent of the sunshine power.

Battery

4. A Li-ion battery with a nominal voltage of 12 Volt and maximal charge capacity (Qmax) of **150 Ah** is used.
5. The battery voltage, V_B, is determined by the state of charge (SOC) according to the equation $\boxed{\mathbf{V_B = V_{B0} + a_B * SOC}}$, where V_{B0} = 11 V and a_B = 1.5 V.
6. The state of charge (SOC) to be kept between **30% to 70%** for the battery's durability.
7. The efficiency in battery charging, η_B, is **95%**.
8. SOC is initially fixed at **60%** at 12 AM on January 1st.

Fuel Cell

9. Fuel cell stack consists of Nc single cells connected in series.
10. Fuel cell voltage, VFC, is expressed by the equation: $\boxed{\mathbf{V_{FC} = Nc *(V_{SC0} - a_{SC} * I)}}$, where V_{SC0} = 0.82 V, a_{SC} = 0.18 Ohm, and I is the FC current.
11. The fuel cell is connected to the battery with a switch and a diode.
12. The voltage of the combined (switch-diode) system, V_{SWD}, is assumed to be **0.7 V** regardless of the FC current.

Load

13. The power demand of four traffic lights with LED lamps is **60 W**.

Inverter

14. The energy efficiency of the inverter, η_{inv}, is **95%.**

Preliminary questions

1.1 The role of the diode in the circuit, shown in Figure 1

By placing the diode in the circuit, we are only allowing the current to flow from the fuel cell to the battery and preventing any reverse current flow. As the diode only passes the current when it is forward biased, so when the battery voltage drops below fuel cell voltage including diode voltage drop, the diode will become forward biased and current from fuel cell will be able to charge the battery while reverse will not be possible.

The diode is typically designed with a low forward voltage drop, which means a minimal voltage loss occurs across the diode. In the given data, the voltage of the combined (switch-diode) system, V_{SWD}, is taken as 0.7 V.

Overall, the diode ensures the proper flow of current and protects the battery from being discharged by the fuel cells when they have a higher voltage.

1.2.1 The main **POWER BALANCES** together with the balances involving voltages, currents, and the battery charge in the system.

Power produced by Solar Panel

The power generated by the PV cells, P_{PV}, is given by:

$$P_{PV}(t) = S_{Irr}(t) * AP * \eta_{PV}$$

Power Produced by Fuel Cell

The power generated by the fuel cells, P_{FC}, is given by:

$$P_{FC}(t) = Nc * (V_{SC0} - a_{SC} * I(t)) * I(t) + V_{SWD}*I(t)$$

The voltage of the combined system (switch-diode), V_{SWD}, is 0.7 V.

Power to be supplied to the Load by Battery

The power delivered to the traffic lights, P_{light}, is a constant value of 60 W.

$$P_B * \eta_B * \eta_{inv} = P_{light}$$

Power balance between Solar, Fuel Cell, and Battery

$$P_{PV}(t) + P_{FC}(t) = P_B * \eta_B * \eta_{inv} + Q_{max*}[SOC(t+1) – SOC(t)] *V_B(t)$$

The above can be transformed into coulomb counting method solved through Euler finite scheme $SOC(t+1) = SOC(t) + I/ Q_{max}$ and the SOC(t+1) can be calculated as:

$SOC(t+1) = SOC(t) + [P_{PV}(t) + P_{FC}(t) - P_B * \eta_B * \eta_{inv}] / [V_B(t) * Q_{max}]$

Here $I = [P_{PV}(t) + P_{FC}(t) - P_B * \eta_B * \eta_{inv}] / [V_B(t)]$

The battery voltage, $V_B(t)$, in relation to SOC is given by:

$V_B(t) = V_{B0} + a_B * SOC(t)$

1.2.2 The logical tests of the two switches to be implemented so that SOC is kept in the above-specified range throughout the year-long run.

To ensure that the state of charge (SOC) of the battery is kept within the specified range (between 30% and 70%) throughout the year-long run, following are the two logical tests that should be implemented for the two switches.

1. PV Cells to Battery Switch:

To prevent overcharging of the battery, the switch should be closed when the battery reaches its upper SOC limit i.e., SOC > 70%.

2. Fuel Cell to Battery Switch:

To prevent battery from hazardous discharging (i.e., SOC<30%), the switch should be closed when the battery SOC drops below a certain threshold. In this case, threshold of SOC<60% has been considered.

1.3 Define orders of magnitude for the ranges of current I and number of cells N_c in the stack to fulfil the steady power demand P_{light} with the above-mentioned battery.

To fulfil the load demand while keeping an account of the solar variations and the battery SOC lower limit, the fuel cell current is assumed, and the number of cells Nc are calculated using the equation below:

$V_{FC} = Nc * (V_{SC0} - a_{SC} * I)$

$V_{FC} = V_B$ (at SOC = 0.6) + V_{SWD}

For the range of PV cells area i.e., (1- 3m^2), below table provides the order of magnitude of current I and number of cells Nc in the fuel cell stack:

PV area (m^2)	Fuel Cell Current	Number of cells (Nc)
1	4.504	1358
2	3.845	99
3	3.19	51

The first case (PV area = 1 m^2) is not an acceptable design as the fuel cell current is at maximum range and the role of PV will not be leveraged which is our requirement. However, case 2 and case 3 are acceptable designs. The proposed design is therefore found through simulation tool in the next section keeping in account the conditions, that are, fuel cell should not remain idle for half of the year and the contribution of solar power should prevail.

1.4 From the whole set of equations and the previously given specifications of the system components, find out how many design parameters must be estimated in the pre-design.

The following design parameters will to be considered in the pre-design:

For PV panel:

1. The area of the PV cells considered to be 2 m^2.
2. Nominal voltage of Solar Panel is assumed as same as the battery equipment i.e., 12 volts.
3. The current and power provided by the sun at each time (hour) over one year is calculated.

For Fuel Cell:

1. The current given by fuel cell is assumed.
2. The number of cells in the fuel cell stack (Nc) is calculated.
3. The voltage of fuel cell is calculated.
4. The power generated by fuel cell is calculated using current and voltage.

For Battery:

1. The operating voltage of battery is calculated.
2. The current and power (using load demand and battery and inverter efficiency) generated by battery is calculated.
3. The initial state of charge (SOC) of the battery is 60%. However, the estimation of SOC throughout the operation is done through coulomb counting method.

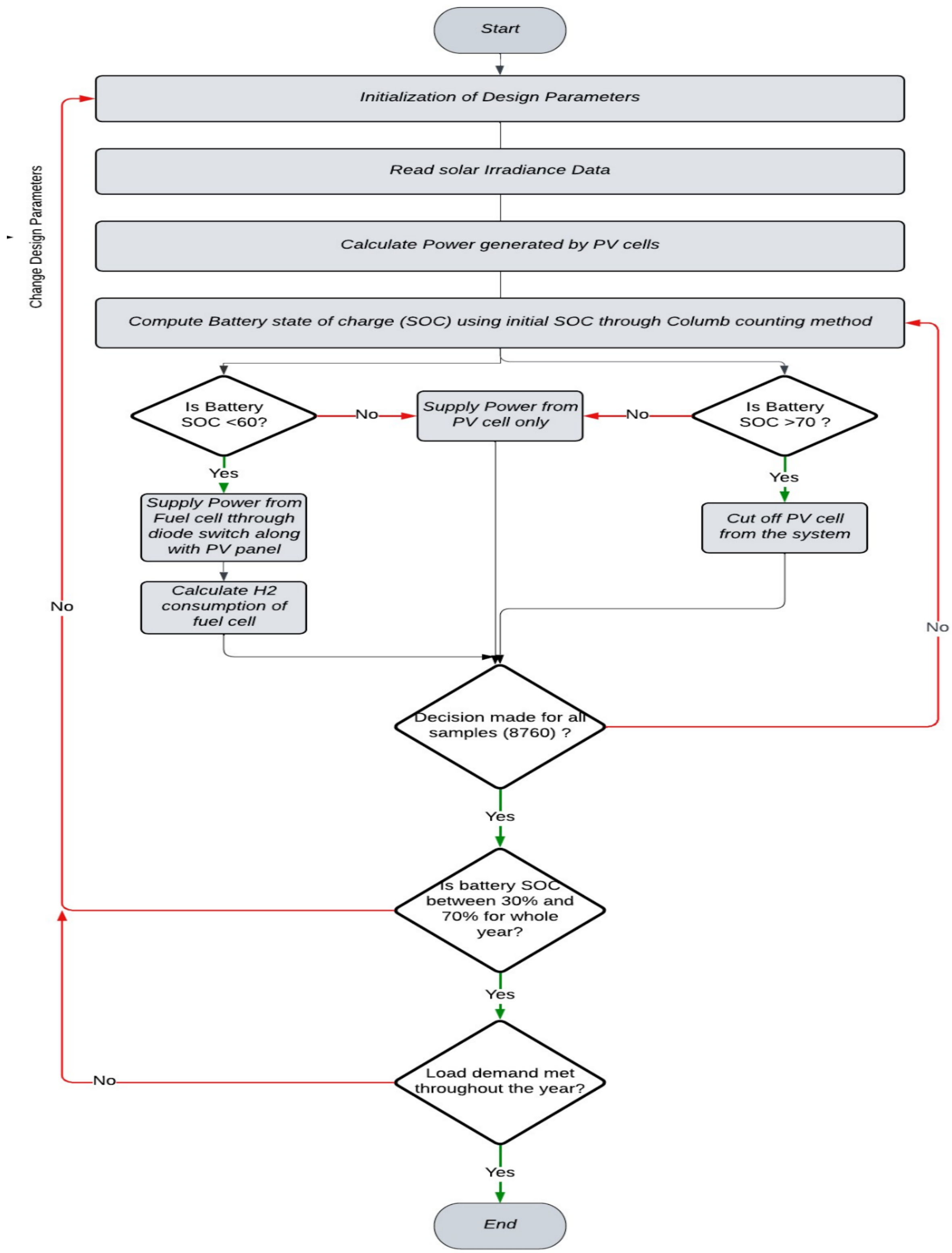
2. Develop the simulation tool, allowing the design parameters involved to be varied manually, with time variations (per hour) of the power contributions of the power source together with that of the hydrogen consumption (in moles or in STP m^3).

In this section, a simulation tool is developed in MATLAB for the Traffic light system in which design parameters are varied manually to meet the load demand throughout the year while balancing the power from the available sources. The design parameters used in the tool are detailed in Table 1 below with a bifurcation of the given parameters and the calculated parameters within the simulation.

The simulation tool provides a basic design of the Nancy standalone Traffic light system providing the parameters for the fuel cell, PV cell, and battery. The design is done in such a way that the system can provide the load throughout the year while incorporating the efficiencies of the PV panel, battery, and inverter. The designed system takes care of the battery's health by keeping the battery SOC between 30% and 70%. To prevent excessive charging, the PV system is cut off when the battery SOC is 70% whereas to prevent the hazardous discharging of the battery, fuel cell generation is incorporated at SOC <60% so that battery SOC will not go below 30% keeping in account the solar variations. The methodology implemented is summarized through the flow chart given below:

The tool can provide a comprehensive review of the power generated by all the sources at each time hour throughout the year. The MATLAB code for the designed tool is given in Annexure A and the power contribution of each source at each timestamp is provided in Annexure B.

MATLAB Program Logic flow chart



Source/ Component	Design Parameter	Description	Unit	Nature
Solar Panel	Irradiance	Hourly solar Irradiance data for 8760 hours	W/m^2	Given
	AP	Area of PV cell	m^2	Given
	η_{PV}	Efficiency of PV cell	%	Given
	Pvoltage	Voltage of solar panel	Volts	Assumed same as nominal voltage of battery
	Solar_Current_to_Battery	Current generated by solar panel	Amperes	Calculated
	Power_produced_by_panel	Power generated by solar panel	Watts	Calculated
Fuel Cell	Vswd	Voltage of switch diode system	volts	Given
	Vsco	Open circuit voltage	Volts	Given
	a_{sc}	ohmic drop across cell	ohms	Given
	I_{fc}	Current generated by fuel cell	Amperes	Assumed
	Nc	No. of single cells in stack		Calculated
	V_{fc}	Voltage of fuel cell	volts	Calculated
	P_{fc}	Power generated by fuel cell	Watts	Calculated
Battery	V_{bo}	Open circuit voltage	Volts	Given
	a_B	No-load voltage drops	Volts	Given
	η_B	Efficiency of battery	%	Given

	Q_{max}	Maximum capacity of battery	Ampere hour	Given
	Battery_Power_Req	Power required by battery	Watts	Assumed same as load demand with efficiency incorporation
	V_B	Voltage of Battery	Volts	Calculated
	I_B	Current given by battery	Amperes	Calculated
	Q	Capacity of Battery	Ampere hour	Calculated
	SOC	State of charge of battery	No unit	Calculated
Inverter	η_{inv}	Efficiency of inverter	%	Given
Load	P_{light}	Load demand (Load Power)	Watts	Given

3. Use the simulation tool to propose an acceptable design of the system (*No optimization*!), avoiding excessive operation of the fuel cell over the year, or on the contrary to avoid the FC remaining idle for half of the year.

<u>Hint: make sure that the average power provided by the FC and that by the PV cells are of comparable orders of magnitude, while privileging the role of PV cells in the power supply.</u>

In this section, the designed parameters finalized for the Standalone system are discussed. By varying the design parameters manually in the tool, the parameters are finalized providing an acceptable design for the system balancing the powers from sources. It is to be noted that the proposed parameters can be further optimized.

The proposed parameters calculated from the tool are given in the table below:

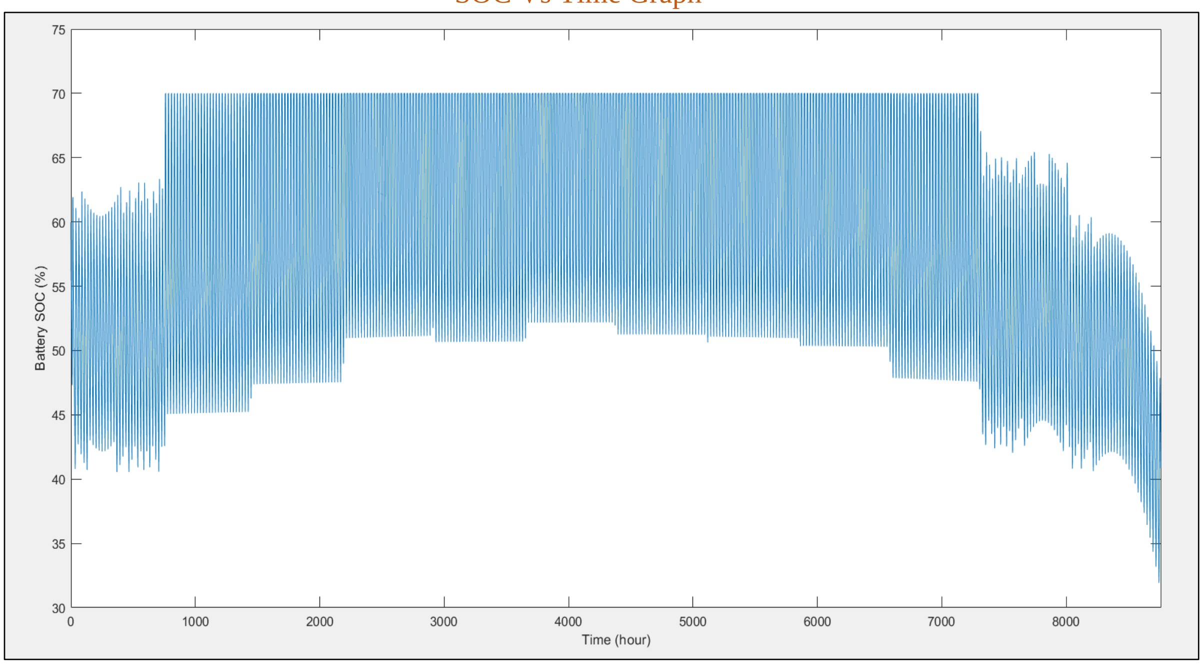
Source/ Component	Proposed Design Parameters	
Solar Panel	Nominal Voltage (Volts)	12
	Yearly Average Current (Amp)	5.15
	Yearly Average Power (Watts)	61.8

Fuel Cell	No. of single cells	99
	Voltage (Volts)	12.6
	Yearly Average Current (Amp)	2.3
	Yearly Average Power (Watts)	29
	Yearly Average Hydrogen consumption (Litres/hr)	20.143
Battery	Voltage Range (Volts)	11.478 - 12.05
	Battery Current Range (Amp)	5.517 - 5.791
	Battery Power (Watts)	66.48
	Battery Capacity Range (Amp hour)	45 - 105
	Battery SOC Range (%)	30 - 70

Following points are to be noted:

1. For the operation over the year, it is to be noted that battery SOC remained between 30% to 70% thus preventing from excessive charging and hazardous discharging. The below graph shows the battery SOC calculated from simulation tool over the year:

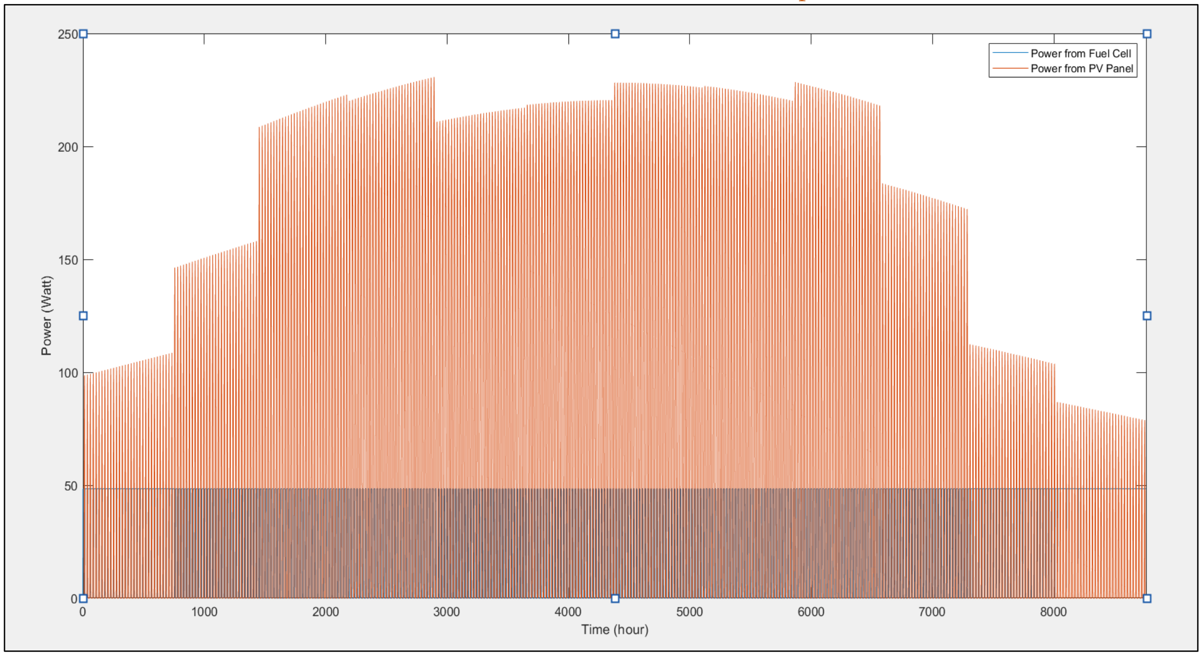
SOC Vs Time Graph



2. The power from both sources produced over the year is shown in graph below. It has been observed that during the case 2 when the no. of cell proposed are 99 and the proposed current contribution is 3.845 amperes, all the requirements of problem statement can be achieved at best. In this case, average power produced by both sources is of comparable order of magnitude while leveraging the role of PV as the fuel cell is used as a backup source to prevent the hazardous discharge of the battery. The average power over the year produced by PV and fuel cell is 61.8 watts and 29 watts respectively showing the same

order of magnitude. While analysing the fuel cell contribution over the year, it is to be noted that fuel cell operates about 60% of the time over the year indicating the acceptable design of the fuel cell as neither the fuel cell has been used in excess nor it remined idle for half of the year.

Solar and Fuel Cell Power Vs Time Graph



4.Search in the internet possible PV cells, battery, and FC stack for the power systems. You may also comment (optionally) on the size of the system and on the relevancy of the standalone in Nancy.

Selection of Solar Panel

- In our case, the maximum solar irradiance of Nancy is around 576W/m^2. Therefore, based on given panel efficiency (20%) and selected panel area (2 m^2), our panel should be capable of harnessing the maximum power of 230 Watts and 19.2 amperes at this power (nominal voltage is 12V).
- Hence, we have selected two monocrystalline solar panels each of 150 Watts with area coverage of 1 m^2 that are to be connected in parallel to achieve the desired output current. (Product Details attached as Annexure C).

Selection of Battery

- To fulfil the design parameters provided in the problem statement i.e., Vmax =12.5 at SOC of 100% and capacity of 150Ah, we have finalized a battery that fulfils our requirement with very high efficiency of 98%. (Product Details are attached as Annexure D).

Selection of Fuel Cell

- The designed fuel cell that fulfils the objectives of problem statement comes with following parameters:
    - Nominal Voltage = 12.6V
    - Efficiency = 48%
    - Maximum Power demand = 52Watt
- We have selected Prtium-50 PEM Fuel Cell that satisfy our requirements and is able to provide the required power along with current. (Detailed Datasheet is attached as Annexure E)

Comment on the relevance of this Solar standalone system to be used in Nancy.

This standalone Solar PV system is considered a suitable technology to adopt in Nancy as it covers part of the electricity consumption going to traffic lights and hence provides a good solution for the decreasing electricity demand in Nancy.

1. Projects in Grand Nancy to reduce energy consumption (www.grand-nancy.org/).

The evolution of Grand Nancy metropolitan electricity and gas expenditure is expected to be spectacular for the year 2023: +316% for electricity and +244% for gas compared to 2022.

As part of the Metropolitan Mobility Plan, the Greater Nancy Metropolis has embarked on numerous structuring projects to enable a global overhaul of mobility uses, and thus meet the challenges of ecological transition, demography, and attractiveness. The objectives are mainly: new fluid mobility, traffic regulation, reconciliation between historical and modern neighbourhoods of the city, environment quality, and green spaces, in addition to reduced energy consumption.

2. National trend in France to adopt Solar power.

At the end of December 2022, France came to a total installed photovoltaic capacity of 16.5 GW. 70% of the newly added capacity came from the regions of Provence-Alpes-Côte d'Azur, Nouvelle-Aquitaine, Grand Est, and Auvergne-Rhône-Alpes. Solar energy is continuing to play an important role in France. The French government has even raised the ambition to reach 44.5GW by 2028.

One of the three largest solar parks in France is Toul-Rosières Solar Park near Nancy. Located in Rosières-en-Haye, it covers 367 hectares of land. With a capacity of 115MW, constructed in 2011, the park has already been in operation since 2012.