Multidisciplinary Project Report

FUZZY LOGIC HYBRID SOLAR INVERTER CONTROLLER FOR PHOTOVOLTAIC APPLICATIONS (FLI)

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Abstract

Since the 1975 - 1990 Civil War, Lebanon's electricity sector has been going through numerous challenges that have made it impossible to have 24-hour electricity. Today, with the country's fuel and economy crises, the situation is becoming unbearable for the citizens as they must pay exorbitant fees for generator subscriptions and still face frequent power outages and blackouts. For many years now, some Lebanese have been relying on photovoltaic energy as an alternative. However, it is somehow expensive and may not be affordable for everyone. So, why not come up with a solution that uses multiple energy sources and toggles between them in a way to provide uninterrupted power supply, while keeping the total cost at its lowest? That is the aim of the project, and it has been achieved by creating a "smart" inverter. In fact, using a machine learning algorithm that takes into consideration the availability of the energy sources as well as their prices, this electronic device was able to choose on its own the most convenient energy source to use. The combined use of a microcontroller with a messaging protocol for the Internet of Things made it possible for the clients to track the inverter's choices through a mobile application. Trial results have shown that the inverter was taking its own decisions - and they were correct – and writing them in a real-time database. Thus, the main purpose was accomplished.

Acknowledgements

Foremost, our sincere thanks go to our manager Mr. Samer Lahoud who made this project possible and gave us the opportunity to work on it.

We would also like to express our gratitude to our supervisor Mr. Robert Farha for his continuous support and understanding while undertaking our research, his patience, his expertise, and his knowledge in the domain.

Finally, we would like to acknowledge and give our warmest thanks to our English teacher Mrs. Mireille Farah for guiding us through all the stages of writing our report, and for her brilliant comments and suggestions.

Contents

List of figures

List of tables

1 Introduction

Since the 1975-1990 Civil War, Lebanon has lacked the capacity to provide 24-hour electricity, leaving many households reliant on their own generators or private neighborhood suppliers who charge exorbitant fees to keep a few lights on or other appliances running during daily power outages that can last several hours [1]. Today, with the economy collapsing, the situation is getting even worse as subscription costs for generators are highly increasing, and blackouts – due to the fuel shortage – are gripping the country and disrupting its citizens' lives. As experts mentioned, this could lead to an imminent "humanitarian catastrophe" [2]. Thus, with electricity becoming a scarce commodity, Lebanese rush to alternative means, such as photovoltaic (PV) energy. In fact, it appears to be the best solution thanks to its flexible configuration, low fuel cost and eco-friendly nature that have rendered it one of the future's major energy sources. However, it is surely not enough to provide continuous electricity so other ones are needed: EdL ("Électricité du Liban" meaning Electricity of Lebanon), power generators, and batteries. The purpose of this project is to provide the clients with uninterrupted power supply (UPS) at a minimum cost. The use of an electronic device – called an inverter – that changes direct current (DC) to alternating current (AC), combined with machine learning, smart devices, and microcontrollers will help achieve this. The project includes an intelligent algorithm developed based on fuzzy logic that will let the inverter choose the appropriate energy source to use at a given time, taking into consideration each one's price and availability. Moreover, the device will be connected to an Arduino board that contains multiple sensors, and a standard messaging protocol for the Internet of Things (IoT) will allow the clients to track and monitor the inverter through a mobile application.

2 Project Facts and Figures

Name	Affiliation	Topic
Majd Abou Assy	Génie Logiciel	Develop the fuzzy logic algorithm and implement the communication with the microcontroller
Joelle Daou	Génie Logiciel	Develop the fuzzy logic algorithm and implement the communication with the microcontroller
Pierre El Hachem	Génie Électrique	Ensure the connectivity between the inverter and the software
Elie Nakhle	Génie Logiciel	Develop the fuzzy logic algorithm and implement the communication with the microcontroller
Fouad Saba	Génie Logiciel	Develop the mobile application and implement the communication with the microcontroller

Table 1- Project members

Meeting Number	Participants	Place	Discussed topics
1	Dr. Farha Majd Abou Assy Joelle Daou Pierre Hachem Elie Nakhle Fouad Saba	Microsoft Teams meeting	Introduction: - Meet the supervisor. - Understand the project as well as its expected outcomes.
2	Dr. Farha Majd Abou Assy Joelle Daou Elie Nakhle Fouad Saba	Microsoft Teams meeting	Follow-up meeting: - Present the Fuzzy Logic research's results and discuss the next steps. - Choose which microcontroller and which mobile application platform will be used
3	Dr. Farha Majd Abou Assy Joelle Daou Pierre Hachem Elie Nakhle Fouad Saba	ESIB – Mar Roukoz	- Present a simulation about the fuzzy logic controller and its components on MATLAB. - Since EdL electricity hours cannot be known in advance, specific hours will be fixed. - The MPPT technique should preferably be avoided.
4	Dr. Farha Majd Abou Assy Pierre Hachem Elie Nakhle Fouad Saba	ESIB – Mar Roukoz	- Present an updated simulation about the fuzzy logic controller and its components with a decision-making solution. - Brief explanation about transforming the MATLAB simulation to an Arduino code and how to make a simulation circuit for the inverter using Proteus.
5	Dr. Farha Majd Abou Assy Joelle Daou Pierre Hachem Elie Nakhle Fouad Saba	Microsoft Teams meeting	- Brief explanation on how the Arduino was connected to the database and how to take decisions based on switches on the Arduino. - Display the application improvements. - Decide which sensors to get for the circuit.
6	Dr. Farha Majd Abou Assy Joelle Daou Pierre Hachem Elie Nakhle Fouad Saba	ESIB – Mar Roukoz	- Test the fuzzy logic algorithm. - Run the application on an Android emulator. - Discuss the circuit and which sensors to use.

Table 2- Project meetings

3 Background/Research

Electricity generation is limited by the availability of fossil fuels and other traditional energy sources. To fulfil current and future energy demands, alternative energy sources should be developed. Photovoltaic energy is a viable renewable energy source, particularly in rural regions [3]. Moreover, it is a DC power source that requires an inverter to convert into useable AC electricity [4]. In addition to that, the principles of a fuzzy logic controller (FLC), as well as its applications and execution, are studied for a PV inverter controller system. Fuzzy controllers, inverter control methods, and switching strategies are all investigated [5]. The findings show that fuzzy logic controls are becoming more popular in power control engineering, particularly in the design of inverter controllers for PV applications and generation [6].

Completeness, redundancy, and consistency may all be checked in the FLC. Finding the bounds of membership functions and other FLC rules, on the other hand, needs manual adjustment, a long calculation time, and a significant amount of work [5], [6]. Future PV applications and generation will necessitate more study and improvement of the inverter system and its control technique. As a result, the focus of this research is on a variety of aspects and obstacles, as well as recommendations for creating competent and efficient inverter control systems for converting PV output to useable AC power using a fuzzy logic controller [7] in order to ensure full time electricity with a low cost.

This project is born from the specific arising case of Lebanon. Different costly supply sources are available yet not sustainable, making it hard to have 24/7 electricity.

Now when it comes to related works, there are many solar energy companies in Lebanon, such as Yelloblue, Solarnet, Earth Technologies, etc. But it seems that hybrid inverters cost much lower and are easier to install.

Furthermore, there is a very common solar charge controller technique that is used: the Maximum Power Point Tracking (MPPT). Its purpose is to maintain the photovoltaic array's operating point at its maximum power point (MPP) and extract the maximum power available. However, it has not been used for this project. Instead, the solution was implemented for the first time ever.

4 Requirements and Constraints

4.1 Functional Requirements

The hardware of the project consists of various sensors connected to an Arduino board. It takes care of tracking the measurement assets by the sensors. These sensors are connected to the inverter to measure the output voltage from the battery before turning the current from DC to AC 220V.

For the software aspect, a mobile application is the way to access these live data and show them. In fact, users will be notified about the inverter's decisions. Moreover, they can track their consumption (daily or monthly) and know how the different energy sources were used. This information comes from the Firebase Firestore Database. Finally, using fuzzy logic that has inputs such as the time, EdL kWh price, generator and the sun, and matching inference rules, this approach can come with intelligent outputs (decision making) such as charge the battery, stop working, etc. This output will be used as an input to the inverter to have a high efficiency (24/7) and most importantly a low cost.

As for the telecommunications aspect, it links the hardware part of the project to the software one. The data collected from the Arduino is first encrypted, then sent to the Firebase Realtime Database through Pyrebase, a Python library.

4.2 Constraints

The first challenge is driven by the environment: in order to have a trained data set, several weather conditions must occur such as sunny, rainy, or snowy. The algorithm will be trained from these conditions and will know how to adapt and act accordingly.

Another challenge is the time. The project must be ready within a period of three months, which might not be fully sufficient. Consequently, the sample that will be implemented might not have the same results in real world.

Furthermore, the fuzzy logic inverter requires different electricity sources, such as EdL supply, private generator, and solar panels. These sources might be difficult to access due to the lack of material and its high cost.

Another concern is the sustainability of the design. It must be reliable, durable, and should survive the diverse conditions, most importantly the various weather conditions. The resources sustainability may form a major challenge as well, as the economic situation in Lebanon is getting worse, making it possible to be left without EdL supply, or even generator supply.

A final limitation of this study is the lack of information in this field since no prior research was made.

5 Project Management

Activity / Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Getting the project	✓													
Define the problem and the goal		✓												
Conducting research and learning			✓	✓										
Implementing the fuzzy model					✓	✓	✓							
Implementing the mobile app						✓	✓	✓	✓	✓	✓	✓		
Connecting the arduino to the inverter									✓	✓				
Simulating our model on proteus									✓	✓	✓	✓		
Testing our prototype and improving it													✓	✓

Figure 1 - Gantt Chart

Predicting upcoming problems and trying to avoid them as possible is a main concern. For that reason, a strategy came up to solve the possible issues. First, the members are all familiar with all aspects of the project so that if a member got stuck or is late for delivering their part, others can help them. Second, a simulation model will be done alongside of the prototype in case some hardware was not delivered on time. This way, it can be ensured of the correctness of the software via the simulator and when possible, it would be implemented on the hardware. Conflicts between group members are possible due to the different backgrounds and ideas, and are susceptible to grow with the increasing tension, stress, and towards the deadline of the project. Thus, it was made sure to collaborate in a healthy environment, while acting as siblings to help each other, communicate better, resolve conflicts as soon as they emerge and reduce stress.

6 Proposed Solution

This section includes the detailed engineering techniques that were used, and the skills acquired throughout the project. It also features a comparison with other alternative solutions.

6.1 Techniques for Engineering Practice

For the software part of the project, a fuzzy logic algorithm was developed on MATLAB having as inputs the availability of the EdL and the generator and their functionalities during the day, the intensity of the sunlight, and the overall charge that the battery acquires. It is important to mention that the prices of the EdL and the generator were fixed as parameters (low, medium, high) over the month according to the economic circumstances in Lebanon.

An important skill needed in this part was how inputs graph could be implemented in such a way that anyone would directly understand the situation and the keys needed in order to obtain a very efficient result. These inputs were chosen based on knowledge and experience.

The middle sector called “Invertor decision” in the figure below was filled with rules that connect every possible combination of the states of these inputs with the result so the algorithm would work based on these rules.

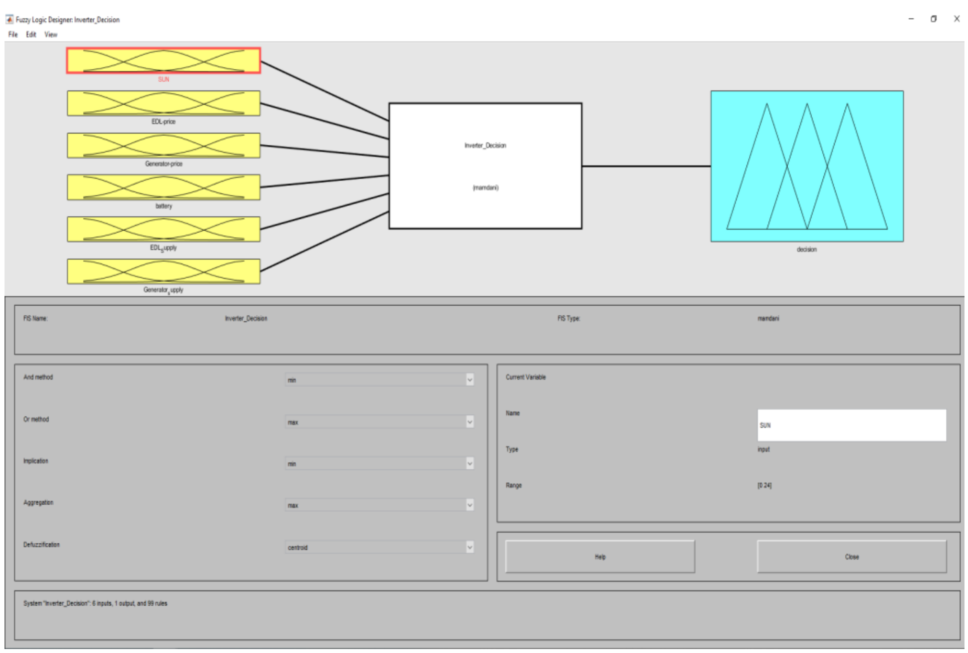

Figure 2 – Fuzzy Inputs

After having the inputs, several rules were introduced based on which the algorithm had to take the decision as shown below. They can easily be modified or deleted.

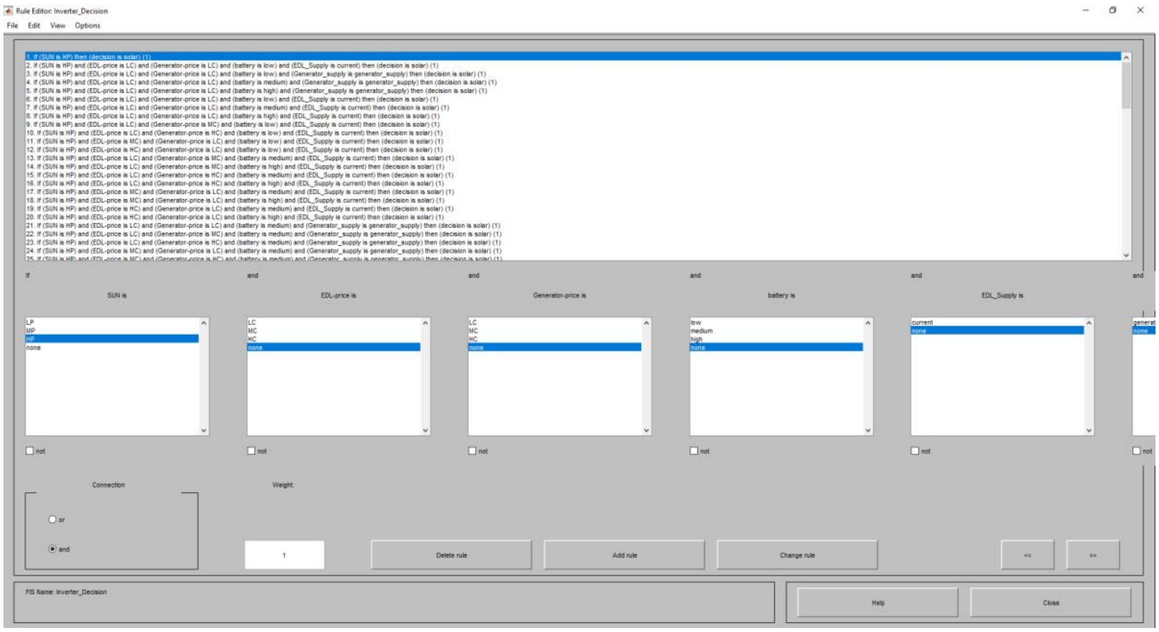

Figure 3 – Fuzzy Rules

The output decision was the electricity source that would be delivered to the house. The X-Axis range was set from 0 to 24 (number of hours). The output variables could be delivered by words (e.g.: “Solar”) or numbers.

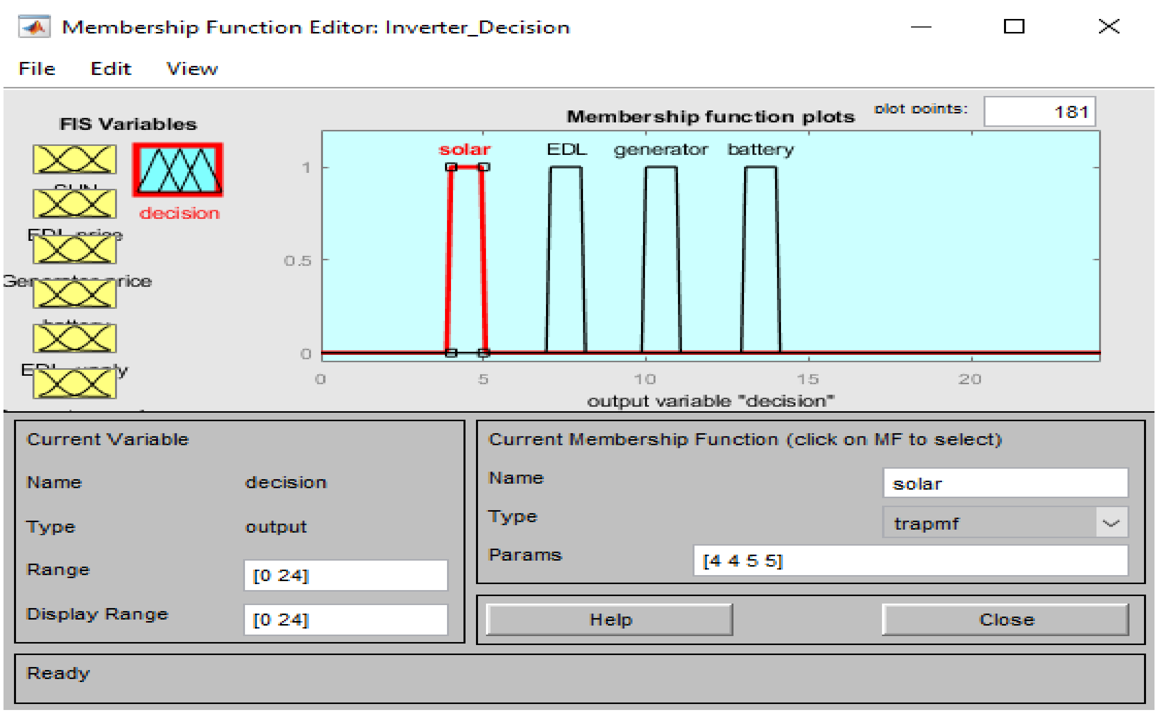

Figure 4 – Fuzzy Decisions

Moreover, a simulation was presented on Proteus software using the Arduino Mega library. Additionally, a mobile application was implemented using Flutter as an open-source framework powered by Dart, a language optimized for fast applications on Android and iOS platforms. This program was designed on Visual Studio Code and simulated on an emulator and an Android device. An authentication guard was developed to control the authentication process for users using Google Firebase. Users can log in using their email account and password.

As for the electronical part of the solution, the sensors were connected to an Arduino Mega 2560 board that tracks the measurement assets. The fuzzy logic algorithm was implemented as a C++ code then programmed to the Arduino's microcontroller using the Arduino IDE.

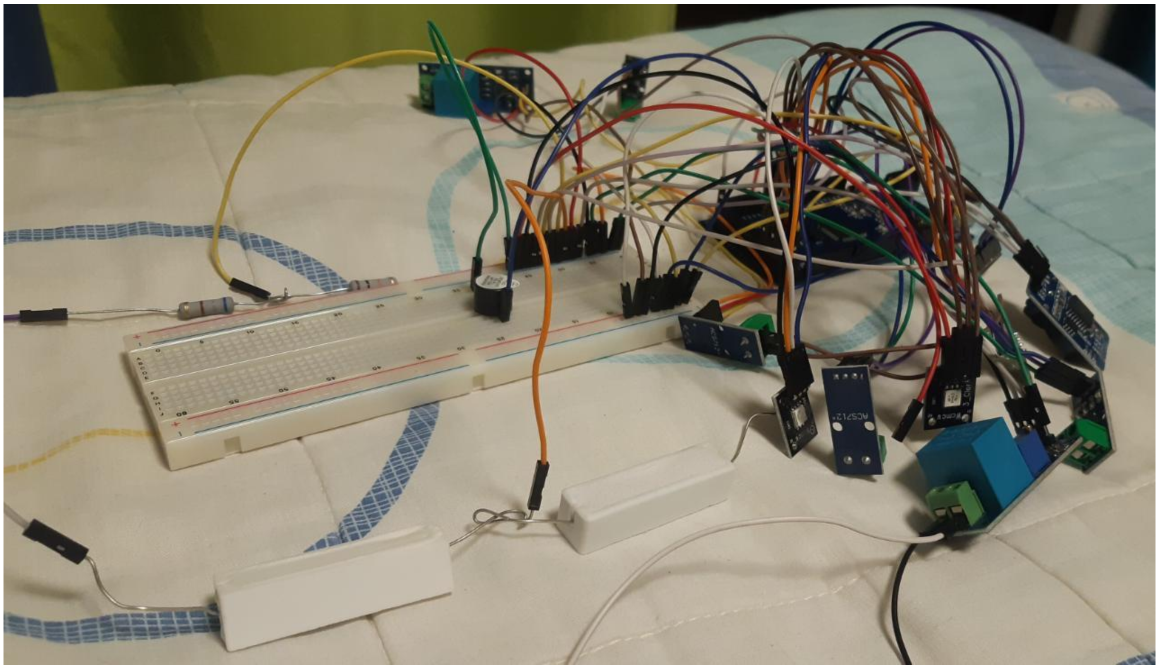

Figure 5 – Electronic Circuit

The system was designed and implemented on a microcontroller-based board and connected to the required sensors. The board chosen is an Arduino Mega 2560, and the sensors are the ones that measure the current and the voltage. The Arduino could have been connected to a computer with a USB cable or powered with an AC-to-DC adapter or a battery to get started. The resistances were used to do a voltage divided from 500V to 5V for the solar energy and from 52V to 5V for the battery. Moreover, 4 RGB LED (Red Green Blue Light-Emitting Diode) were used to notify about the source that was being used. Additionally, an easy way to build the circuit on a breadboard was provided by the Male-to-Male Breadboard Jumper Wire. These cables were flexible for creating circuits between the microcontroller and the breadboard.

As for the telecommunications part, using Python, the Arduino was connected to Firebase – a specific platform for mobile applications and websites – then the data collected from the Arduino was encrypted, creating a Realtime database so it could be converted to a JSON (JavaScript Object Notation). The data was then retrieved by the application and added to the correct field so that the users could visualize it.

As already mentioned, the Flutter framework and Firebase database were used for the mobile application development. Everything was thoroughly implemented. The main goal was to enhance the users' experience while using it. Thus, it is very user-friendly and intuitive.

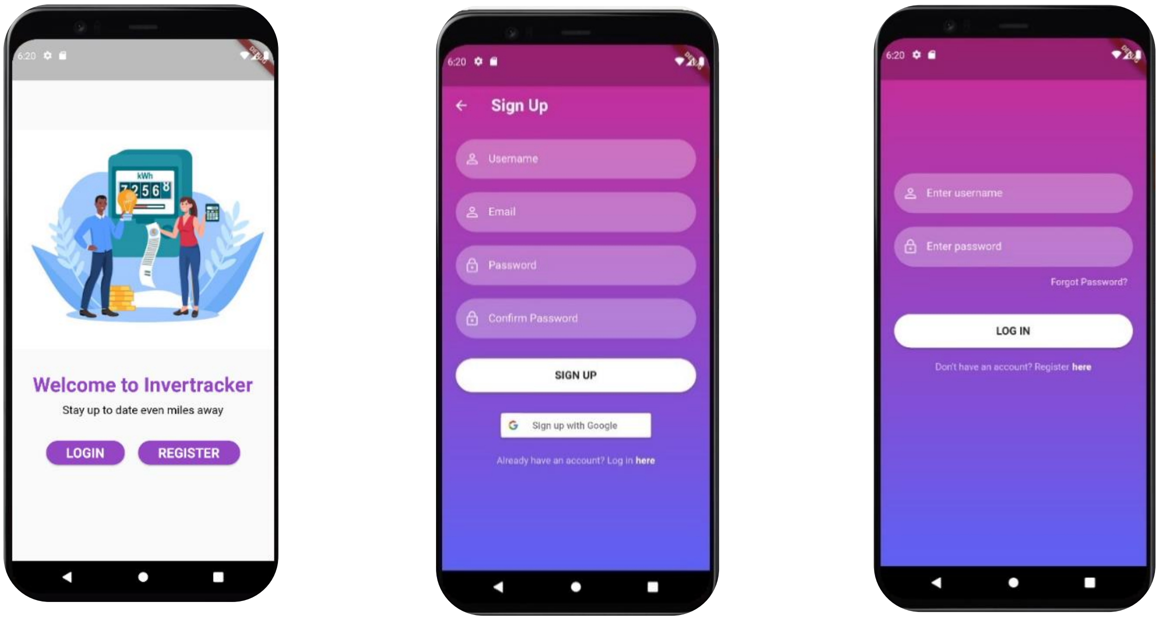

Figure 6 – Authentication Interface

This section allows users to visualize their monthly consumption, as well as their savings.

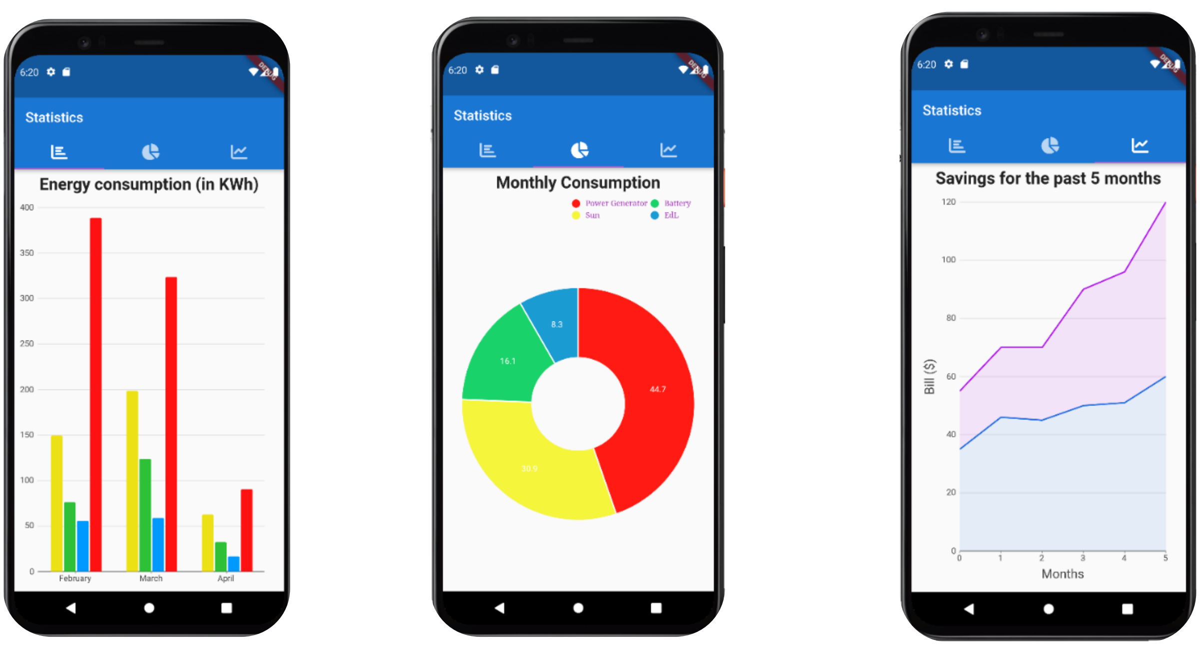

Figure 7 – Statistics Interface

Had it not been for the hybrid inverter, the monthly electricity bills would have been much higher.

Figure 8 - Dashboard

The current performance of the photovoltaic (PV) generation and consumption of the users' home, the forecast time of Beirut, the production, and the consumption estimation of the next four days are displayed on the page "Dashboard".

The current percentage of the users' battery with an icon of its state are represented in green (full mode) if it is higher than 20% and in red (discharging mode) if lower. The icon's battery is shown in blue (charging mode) if users are charging their phone. Moreover, the photovoltaic generation's power is displayed in the purple chart in kilowatts [kW] over the day under the formula **P = U x I [kW]** [8] using sensors for current voltage and current of the solar panels. Therefore, the more sunlight the solar panels will receive, the more energy will be generated. Additionally, the consumption is shown in the blue chart using the same formula with sensors to calculate the consumption of the users' home over the day. A backup mode using the battery system is used in case the production of the PV generation is lower than the consumption. All of the previous are arranged in the top container.

Furthermore, the weather predictions for the four next days is displayed in the bottom container using the OpenWeatherMap API (Application Pogramming Interface) [9] along with forecast solar generation and forecast consumption. The expected solar energy production and consumption are shown as well. These projections are based on historical production and consumption data from the past months.

6.2 Skills for Engineering Practice

It is undeniable that one of the most crucial skills an engineer can possess is strong problem-solving abilities. During the past three months, many challenges were encountered, whether it was on a hardware or software level. Fortunately, they were overcome by finding alternatives every time.

Another important skill developed throughout the project was teamwork. It was the first time that members from different domains work together, and it was an introduction to what might be faced in the future engineering careers.

When it comes to the fuzzy logic algorithm, the research had to be done for the first time ever. During that process, programing skills on MATLAB and C++ were reinforced to successfully implement the model using the algorithm and its methods. Moreover, this algorithm's implementation could not have been made without high critical thinking abilities that include conceptualizing, applying, analyzing, synthesizing, and evaluating information.

In addition to that, working with the Flutter framework - on which the mobile application was deployed - was at first a challenge. This contributed to another skill being acquired: programming in Dart.

Furthermore, manipulating the Arduino and knowing how to connect it to the components, how to send signals, how to send data and process it was another major skill learned.

During the project, there were times where parts of the project were not delivered on time, so other parts would be delayed. The help was quickly delivered where it was possible and in other cases the solution was to be wait. This led to acquiring two important skills: perseverance and patience.

6.3 Comparison with Alternative Solutions

For many years now, some Lebanese citizens have been opting for photovoltaic energy and solar panels. However, this solution is most probably more expensive than the one implemented. In fact, solar panels are costly because they require experienced installers and use enormous volumes of high-purity silicon [10].

Lebanon's situation is undoubtedly a very particular one. Hence, there is no other place in the world that uses the same energy sources as the generator and the EdL, so the hybrid solar inverter controller developed is one of a kind. However, some other hybrid controllers were done using different resources. In their recent study, a team in the electrical department of "Millia Institute of Technology, Purnea (Bihar), 854301 in INDIA", implemented a hybrid controller for PV-Wind-Fuel sources [11]. The Team used a Firefly-Asymmetrical fuzzy logic controller that decides the source of power based on its heuristics [11] similarly to this project that also uses the fuzzy logic algorithm. The main advantage of the hybrid solar inverter controller was the significantly lower implementation cost, since Lebanon is going through an economic crisis and it is becoming hard to have a high-cost project, it is the better solution for the situation and the most practical one.

7 Testing and Improvements

7.1 Testing and Fine-tuning the System

During the fuzzy logic implementation, frequent testing was conducted to find the best estimator of the decision, knowing that in the project, it is precisely hard to detect it. Since it was hard to find the appropriate data to assign the input values, they were based on knowledge and experience. The rules were tested to make sure of their correctness.

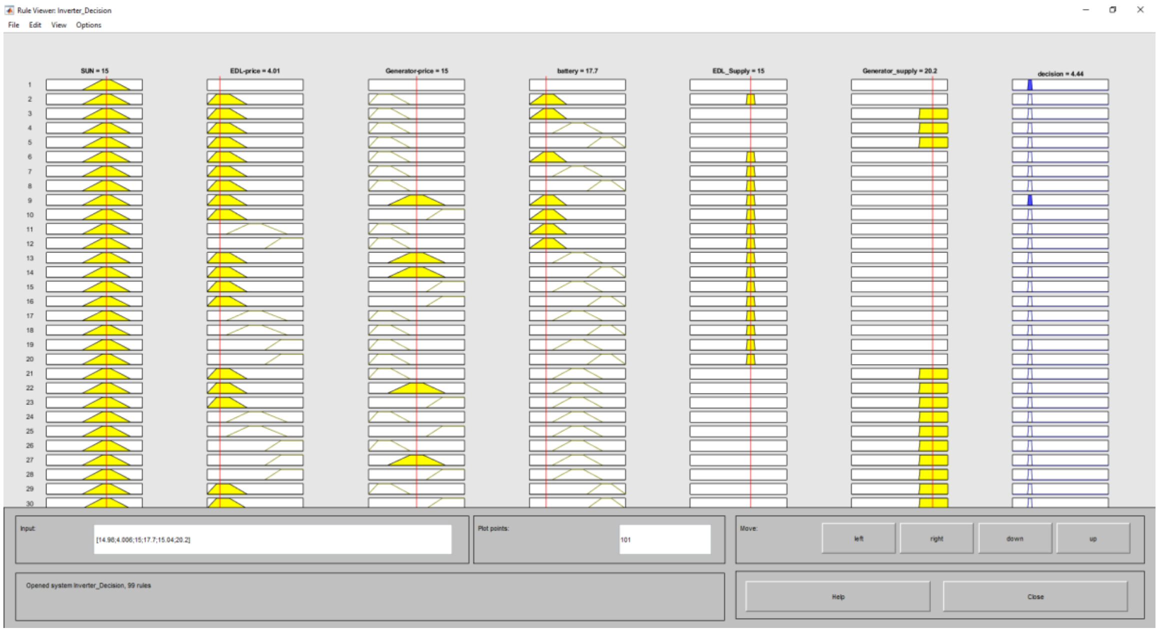

Figure 9 – Testing Rules

The project uses different kind of sensors that were tested to ensure the completeness of the system. And after that each one was on the specific pin according to the Arduino code that is implemented using fuzzy library named “eFLL” (Embedded Fuzzy Logic Library). After the successful compilation of the code (fig.4), the output was tested to make sure that it matched the value after defuzzification using MATLAB. The work was pursued by checking if the value was in a specific range. The decision would be confirmed if it was acceptable and rational.

While processing and making sure that the connection between the Arduino board and the MQTT server is good, the sensors collected the appropriate data. Dummy data was sent to an MQTT monitor and checked if these data would be received successfully or not. Also, the Arduino board was connected to the internet using Ethernet cable.

The clock was set for the Arduino board, knowing that the project needs to know the actual hour in order to take the best decision. The day of the month was also set to know the actual price of the Kilowatt-hour [kWh] of the electricity by knowing the consuming average of it.

After further research and testing, it was found out that Arduino could be connected easily to the application. So, another modification was made. The MQTT server solution was removed, and a python code was developed.

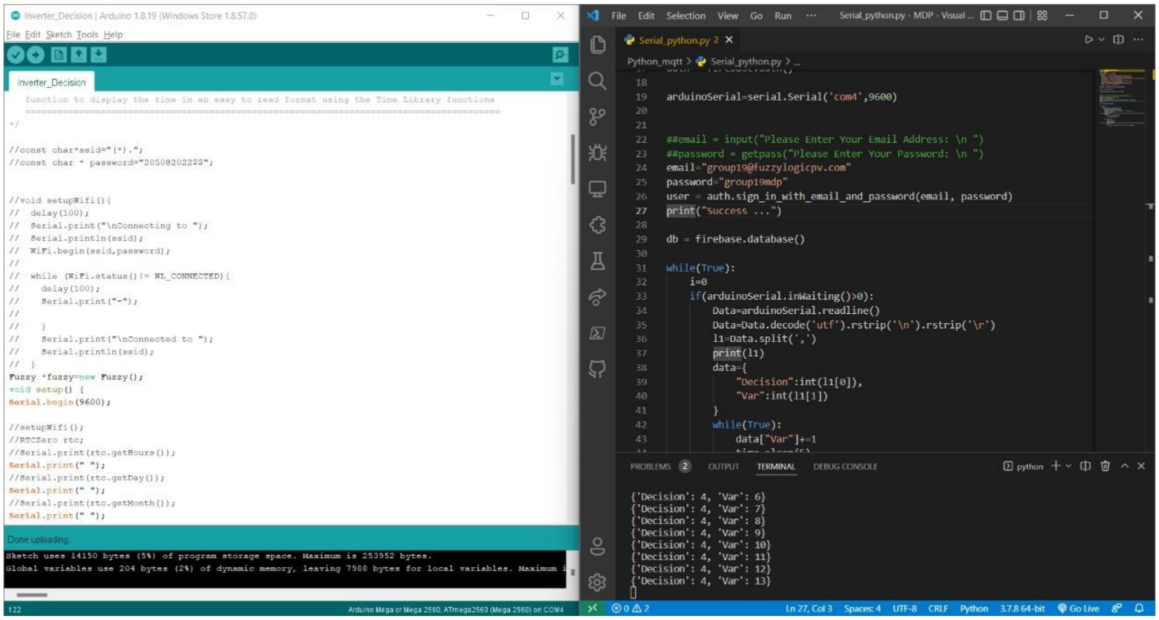

Figure 10 – Arduino and Python code

The code would retrieve data from the Arduino, take the decisions each time slot and then assign them different IDs to differentiate them. These outputs would eventually be transformed to a JSON and transmitted to firebase. This was made possible by making the Python code use the laptop's Wi-Fi. In Firebase, a new project was created to be able to get the data and use it. The project has an email/password authentication.

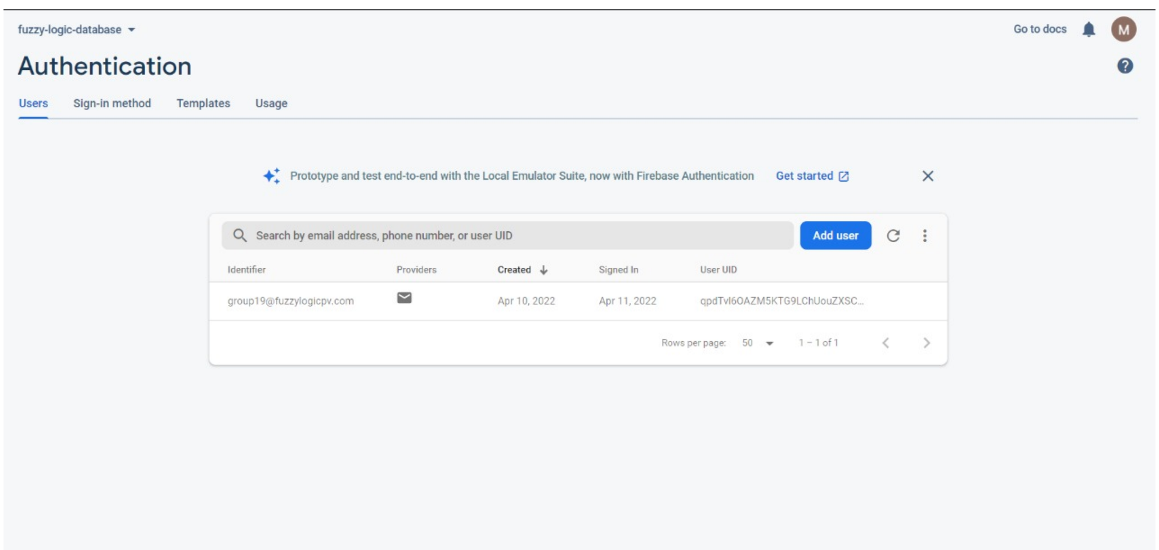

Figure 11 – Firebase Authentication

The Realtime database retrieved from the Arduino code is then used in the application to visualize data.

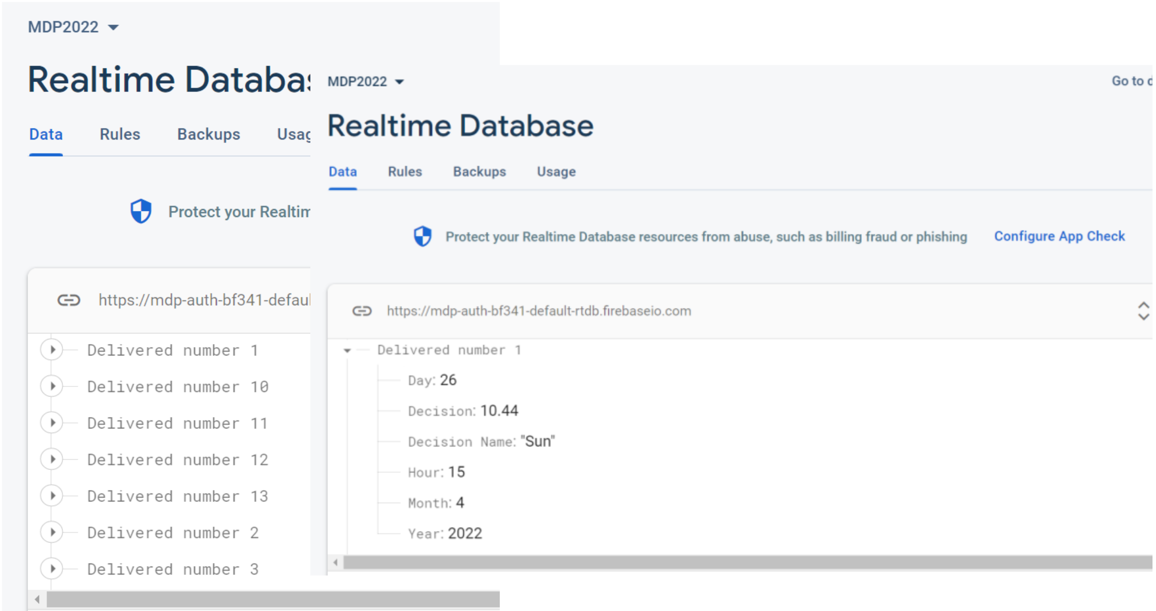

Figure 12 – Realtime Database

Another improvement made successfully was the transformation of the C++ code. The "eFLL" was no longer in use and a new script was made (fig.13). The script has all the rules implemented on MATLAB, takes the actual time, and gives the result as a string on an LCD board connected to the Arduino, as well as turns on an RGB light (fig.14). The color of the light is given according to the decision (fig.15).

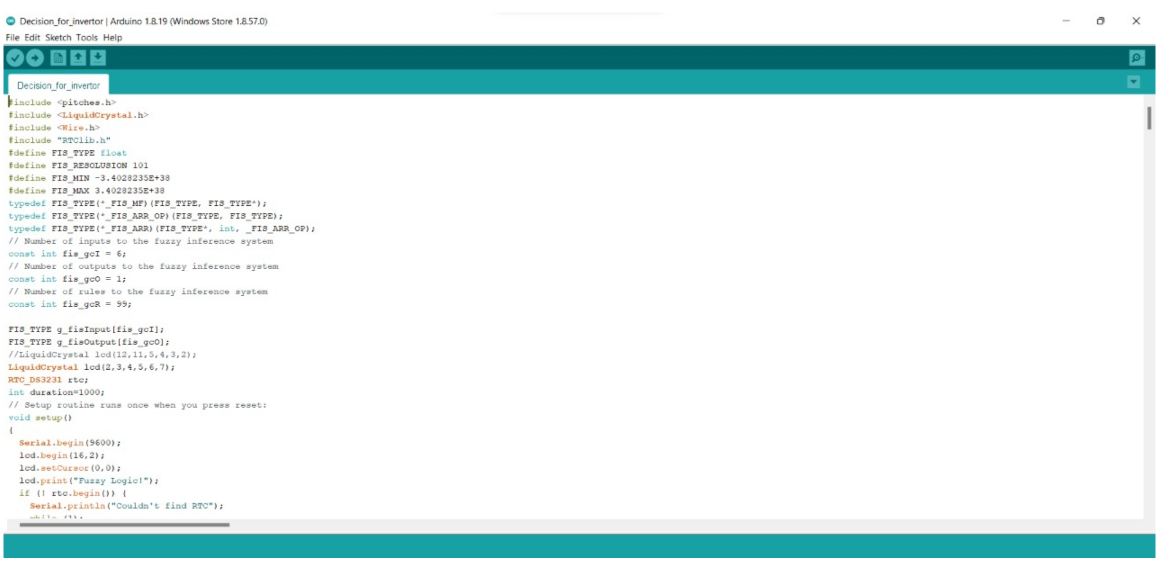

Figure 13 – New C++ Script

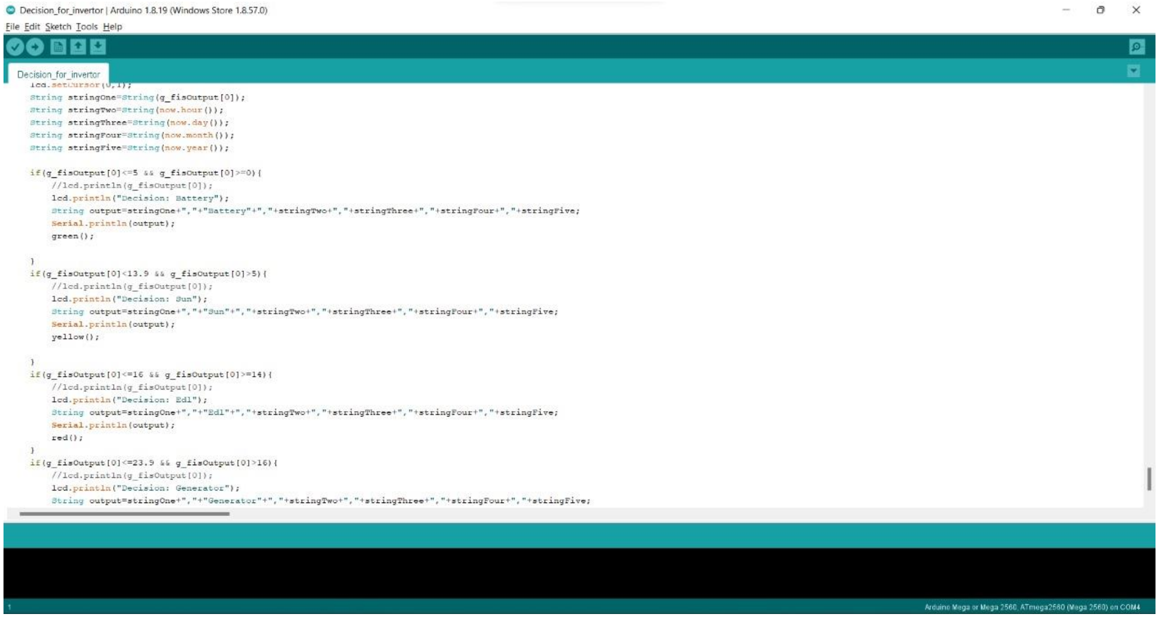

Figure 14 – Delivering the Decision

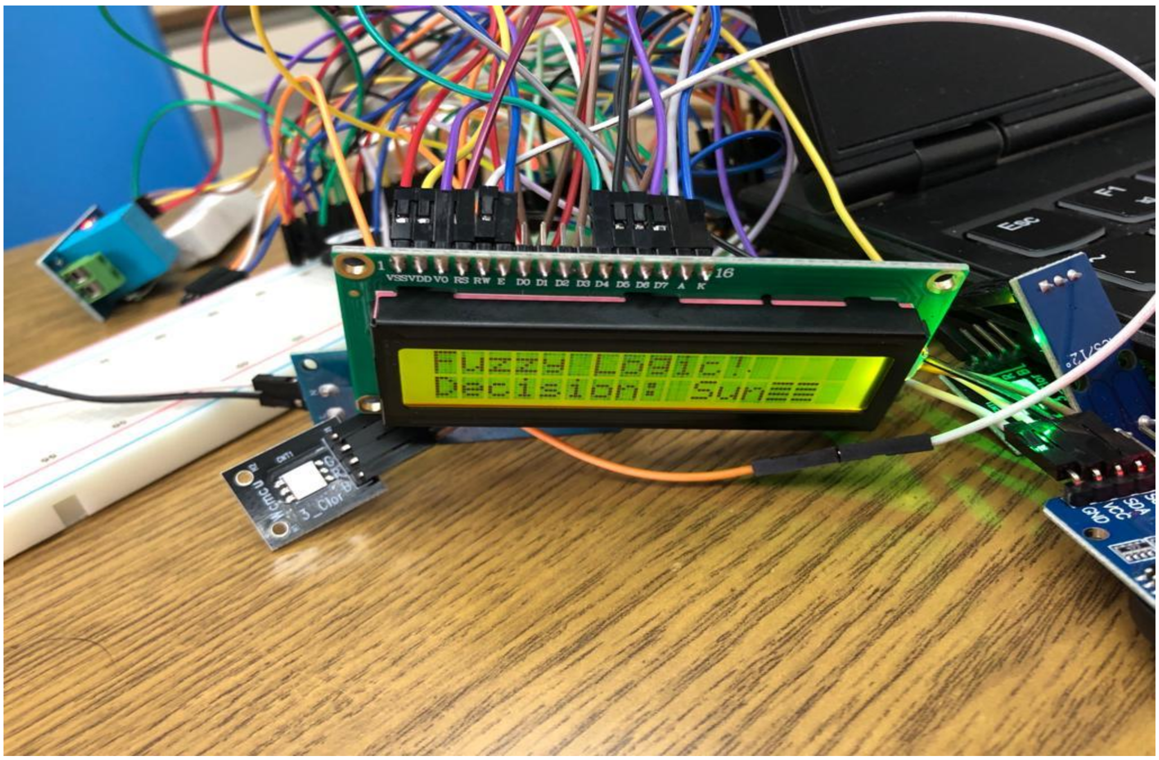

Figure 15 – Example of the Decision on the LCD Board

Now on the application level, the code was compiled and run again after every modification, no matter how significant it was. Moreover, Dart's null safety guaranteed that no object references would have null or void values that would entail an application crash.

The success of the authentication process was made sure of by creating new test users then signing in with their account (fig.11).

For the consumption statistics, before the data was retrieved from the Firebase Realtime Database, it was static: the calculation was based on the average monthly sun hours in Beirut [12], as well as assumptions about the battery percentage and the EdL hours.

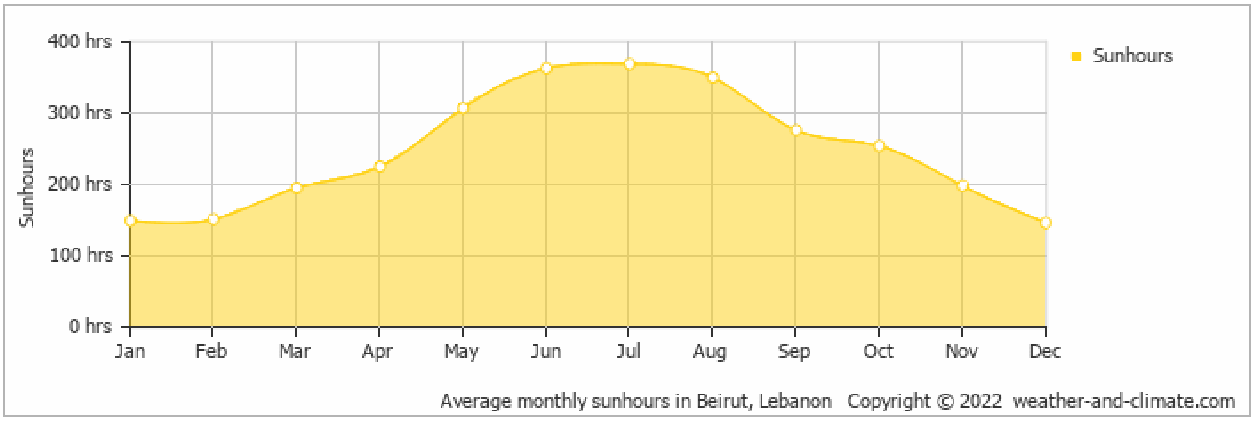

Figure 16 – Average Monthly Sunhours in Beirut

7.2 Possible Improvements

With more given time and friendlier work circumstances, the project could be improved with some additional features.

At the Machine Learning level, the input data could be done using neural network to make a huge dataset of which the size could reach more than a million.

When it comes to the fuzzy logic algorithm, it would have been better if all the implemented rules had been used. This would have optimized the inverter's decisions. However, it was hardy feasible due to their huge number.

The mobile application can always be upgraded with new features and options, upon users' requests. One possible additional feature could be battery tracking (charging, usage, statistics, etc.)

8 Impact of the Solution

Lebanon's electricity sector has been going through numerous challenges that have rendered it notoriously dysfunctional for the past three decades. Today, as a result of the country's fuel and economy crises, the blackouts are harming all sections of society: hospitals, restaurants, households, etc. [13] Therefore, a hybrid inverter is believed to be the best solution to satisfy the needs of the Lebanese people: it would not only provide them with 24-hour electricity but would also ensure a minimum cost. This would improve their welfare and their living conditions that have been deteriorated and impoverished for a very long time now and give them hope in a country where there seems to be none left.

Furthermore, the solution turns out to be eco-friendly. First, it has been proven that solar energy emits significantly less pollution than other alternative energy sources [14]. In addition to that, it contributes to decreasing global warming and greenhouse effect: in the process of transforming light into energy, solar panels have zero emissions. Experts have even stated that a solar panel with a projected lifespan of 28 years could eliminate carbon dioxide emissions by more than 100 tons [15].

9 Conclusion

In conclusion, this project was undertaken to provide a 24/7 electricity supply to Lebanese people, using different energy sources such as EdL, private generator, solar system, and a battery, and ensuring the least possible cost. This model comes with an application installed on the customers' phone that notifies them about the different states. An intelligent fuzzy logic design was developed to efficiently choose the right power supply over the day taking into consideration the lowest price. The design was implemented through MATLAB and integrated into an inverter using an Arduino board that ensured the flow of data and connectivity to different power sources so that the algorithm could choose the right supply source. The data was also delivered to the application so it could be displayed to the users. Prior to this study no other model was made to choose between the different power sources in Lebanon, which made the project of a high importance due to its great impact on the society.

Despite the challenges faced and the harsh circumstances, we were able to attain our objective: the inverter was effectively choosing the appropriate energy source at a given time, and the mobile application was successfully implemented. Perseverance, dedication, and teamwork were the key to our success. With more time and more data at hand, we aim to further improve our project.

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