Simulation software for heat and power cogeneration (CHP) using green hydrogen

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***Abstract*—Energy transition offers a wide range of benefits, including the potential to confront the recent energy crisis. Green hydrogen is a fast-developing clean energy source due to its low carbon emission in the atmosphere, promoting, thus, not only significant economic growth, but also independence from fossil fuels. Raising the public's awareness about renewable energy sources can lead to social acceptance and the rise of green practices, leading to the assimilation of such practices into everyday occurrences. To increase these practices and educate both students and the public about renewable energy, the role of educational establishments is considered essential. An effective tool to spread awareness and provide insight about green hydrogen is through specialized simulation software. In this paper, an interactive dashboard is realized to examine, to a certain extent, how a hybrid battery-hydrogen storage system operates and satisfies different energy needs, using photovoltaics, water electrolysis and fuel cells, implemented using Microsoft Excel® and its integrated tools. By processing a sample of load data originated from a hotel located in Heraklion, Greece and some user-defined variables, the software calculates hourly values including hydrogen and thermal production in an annual basis.**

Keywords—STEM, Simulation software, educational software, hydrogen, heat cogeneration, CHP, heat recovery, storage system, hybrid system, photovoltaics, RES technologies

I. Introduction

The role of educational institutions is considered crucial to the increase of awareness and the understanding of emerging technologies. Different methodologies are developed striving to increase the technical knowledge of professionals ([1-2]) or inform the general public in technical matters that could benefit their everyday lives. The use of renewable energy sources (RES) is becoming increasingly widespread. Green energy technologies enhance economic growth and achieve independence from fossil fuels, using clean and sustainable energy instead. Despite its importance, many people are still unaware of the potential of renewable energy sources. Awareness is an important factor regarding the fight of climate change, since social acceptance and support of rising green technologies is essential to their eventual integration in everyday life. It is imperative that governments openly implement and support policies on all educational tiers that inspire actions and training towards green energy practices [3].

Green hydrogen technology is a developing and promising method of efficient energy storage system, potentially serving as a clean energy source due to its low carbon emission in the atmosphere, aiming to increase RES penetration through carbon-free energy storage. One way to raise awareness about green hydrogen is through specialized simulation software. It has been proven through extensive research that using a software system to support in-class learning helped students understand the subject better [4]. Furthermore, in research conducted in Turkey, teachers confirmed that a combination of different software educational programs, teamwork and motivational skills increased the students' performances [5]. So far, user-friendly simulation software intended for both educational purposes and optimization of simulated systems have been developed, providing encouraging results ([6-7]). Thus, this simulation software can help students understand the basic concepts of a hydrogen system and also increase their interest in renewable energy sources in general.

Using Microsoft Excel® and its built-in tools, an interactive dashboard was created in which users have the opportunity to understand to a certain extent how green hydrogen is produced, stored and distributed using photovoltaics (PVs), fuel cells, battery, heat pumps and water electrolysis. Moreover, in this software it is also explained how thermal energy can also be produced with a heat exchanger by taking advantage of the system's losses. Real data was used to make the necessary calculations originating from a hotel located in Heraklion, Crete. By using the data and some user-defined variables, the software calculates hourly values, aiming to provide accurate simulation of an actual system, accompanied by metrics determining the system's overall efficiency.

II. Dashboard Development

For the purposes of this paper, *Microsoft Excel®* was used for the development of the simulation. The primary components of the file are consisted of the dashboard, accompanied by the control panel containing the variables defined by the user, and the values calculated using the algorithms described by the methodology as described in detail in section III. The dashboard, also, displays charts portraying the efficiency of the system. In Fig. 1, the dashboard is displayed, containing the simulation's features.

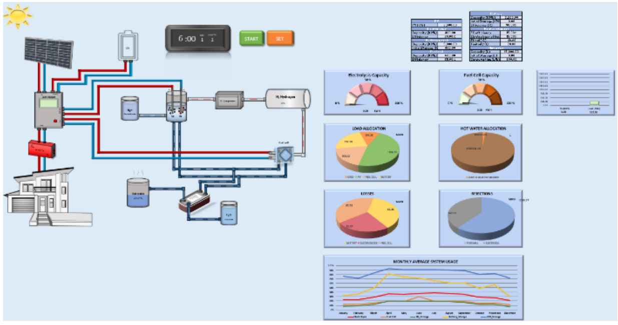

Fig. 1. Dashboard overlook.

Using the software's built-in objects, different components such as PVs, fuel cells, cables etc. have been designed to provide a visually comprehensive environment. The red cables represent the positive flow of electrons and the blue ones the negative according to the conventional current flow. The controller is the system's component which controls and allocates the generated power. The controller is also connected to the inverter to convert direct current (DC) to alternating current (AC), to be distributed to the building's infrastructure to satisfy its energy needs. The system also has two distinct energy storage systems to store surplus energy, a conventional battery system, and a hydrogen system based on electrolysis. In Fig. 2, the designs of the PV system, the controller, the load infrastructure and the conventional battery are presented.

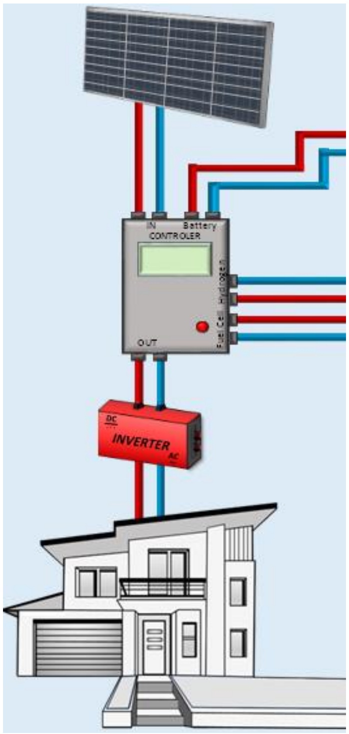

Fig. 2. Depiction of PV and conventional battery subsystem.

The hydrogen system consists of an electrolyzer, the container where the phenomenon of electrolysis occurs, in which an aqueous solution produces O_2 and H_2 [8] in gaseous state, the fuel cell (FC), compressor, and hydrogen tank. After the H_2 is produced it passes through the compressor which compresses the hydrogen to minimize its volume. The compressed hydrogen is then transported to the hydrogen tank for storage. When the system cannot satisfy its energy needs through PV production alone, it produces electricity using the fuel cell with the use of hydrogen as fuel (in case of sufficient hydrogen storage). The last subsystem of the simulated system is the one that produces thermal energy. This subsystem has two major components: the hot water tank, where thermal energy is stored in water, and the heat exchanger (HE). The heat exchanger takes advantage of the system's losses stemming from both the FC and the electrolyzer. A portion of the heat that would be produced during a chemical reaction occurring in the FC's or electrolyzer's chamber and lost to the environment is, instead, used to increase the temperature of water contained in thermally-insulated tank, filled with water originating from the water supply system. In Fig. 3, the hydrogen and heat exchange subsystems are depicted as drawn.

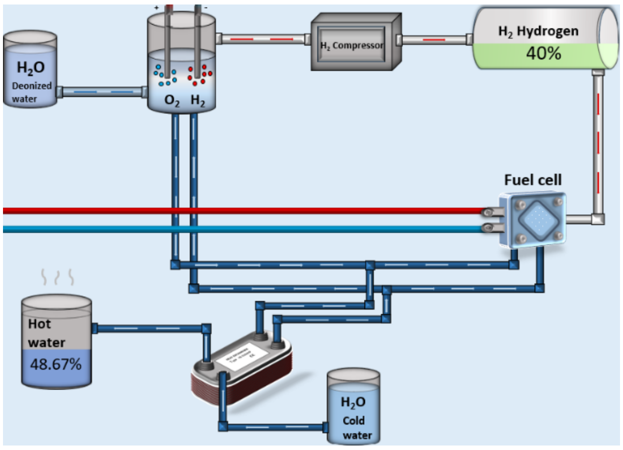

Fig. 3. Illustration of hydrogen production and heat exchanger subsystems.

The dashboard includes a control panel which contains the technical characteristics of the system's components, permitting the accurate modeling of distinct system designs and implementation. The fist parameter is the installed power of the PV in standard test conditions (STC). The next three parameters concern the conventional battery and are the capacity, the efficiency, and the initial battery storage. Both the electrolyzer and FC have each two parameters which are capacity and efficiency. The hydrogen tank and hot water tank have, also, similar parameters which are their total capacity and initial storage. The last four parameters are related to the heat exchanger's function and the thermal energy that is produced. Two of these parameters are the heat efficiency of the FC and the electrolyzer. This efficiency is equal to the portion of the input electrical energy that would be successfully stored as thermal energy in the water tank. The last two values regulate the initial and final temperature of the heated water, while a fixed hourly hot water consumption within the premises is set. In Fig. 4, the control panel is illustrated, designed for ease of use.

PV	
PV (KW)	5,000.00
Electrolyzer	
Capacity (KWh)	250.00
Efficiency	80.00%
Hydrogen tank	
Capacity (KWh)	1,000.00
Intial Storage (KWh)	100.00
Fuel cell	
Capacity (KWh)	250.00
Efficiency	80.00%

Battery	
Capacity (KWh)	2,000.00
Intial Storage (KWh)	0.00
Efficiency (%)	80.00%
Heat exchanger	
FC efficiency	10.00%
Electrolyzer efficiency	15.00%
Tfinal (°C)	40.00
Tinitial (°C)	20.00
Hot water	
Capacity (L)	100,000.00
Intial Storage (L)	0.00
Consumption (L/h)	500.00

Fig. 4. Dashboard's control panel.

III. METHODOLOGY

The implementation of the aforementioned features requires certain data, such as the hourly demand, the normalized PV production [9], and the values as set in the control panel. In Fig. 5, the input of the electrolyzer is calculated, based on the previous data.

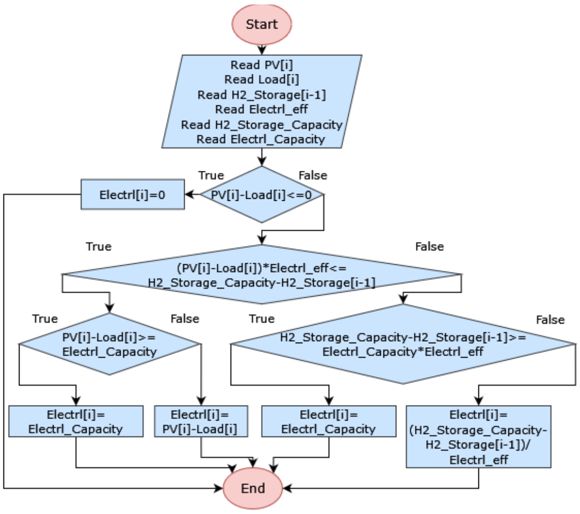

Fig. 5. Electrolyzer flowchart.

In Fig.6, the output of the fuel cell is calculated, in case of insufficient PV production for load satisfaction, or in case of low battery's state of charge, increased by hydrogen-produced power for peak load satisfaction. Both cases require ample hydrogen storage.

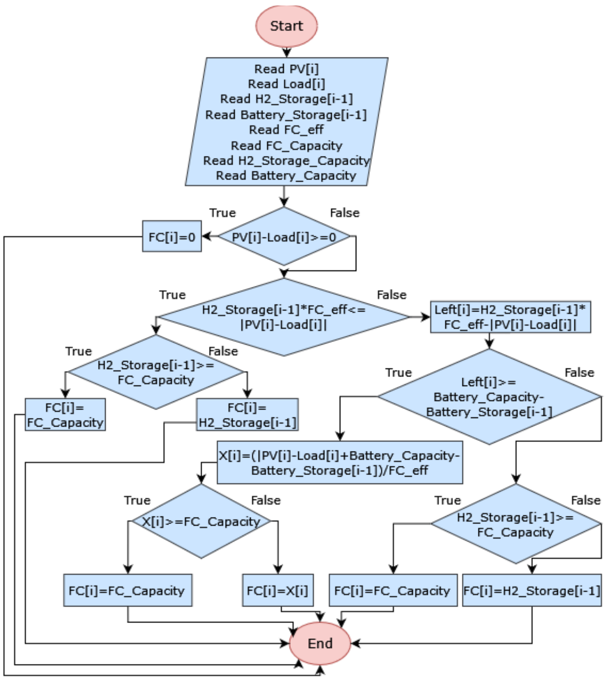

Fig. 6. Fuel Cell output flowchart.

In Fig. 7, the hydrogen tank's state of charge (in energy units) is calculated after each hour.

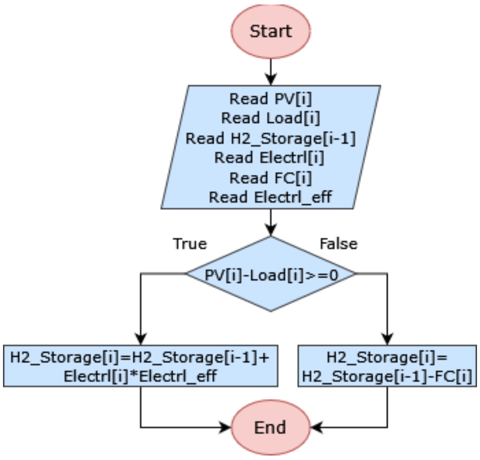

Fig. 7. Hydrogen tank storage flowchart.

In Fig. 8, the battery storage is computed. Discharge takes place in case of both PV and fuel cell insufficient participation in load coverage, while charge takes place when there is both surplus of PV production and increased hydrogen tank's state of charge, or in case of charge stemming from the fuel cell for future peak load satisfaction.

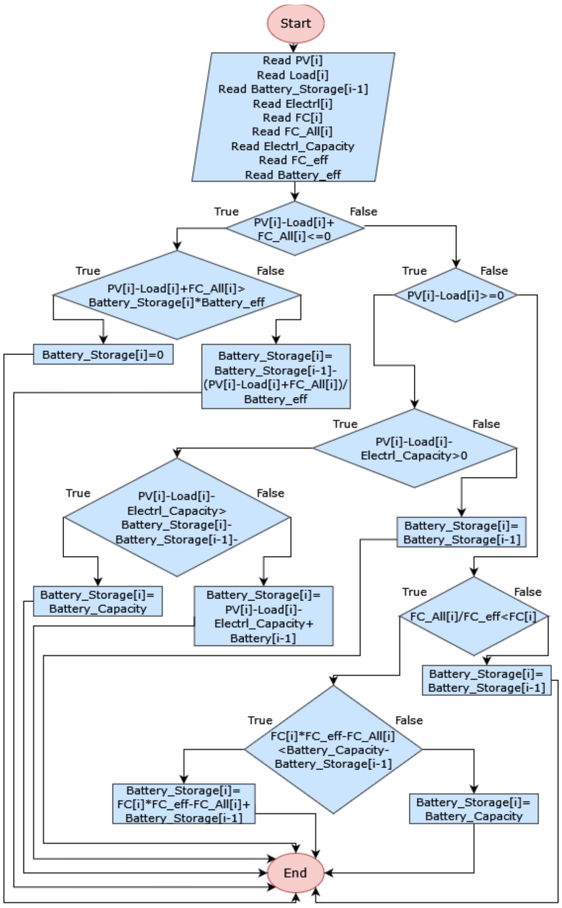

Fig. 8. Battery storage flowchart.

In Fig. 9, the contribution of PV in direct load satisfaction is calculated.

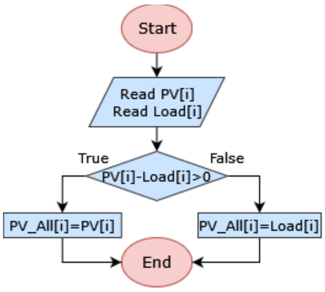

Fig. 9. PV allocation flowchart.

In Fig. 10, the fuel cell contribution to the load is calculated, the discharge resulting in increase of the battery's state of charge being neglected.

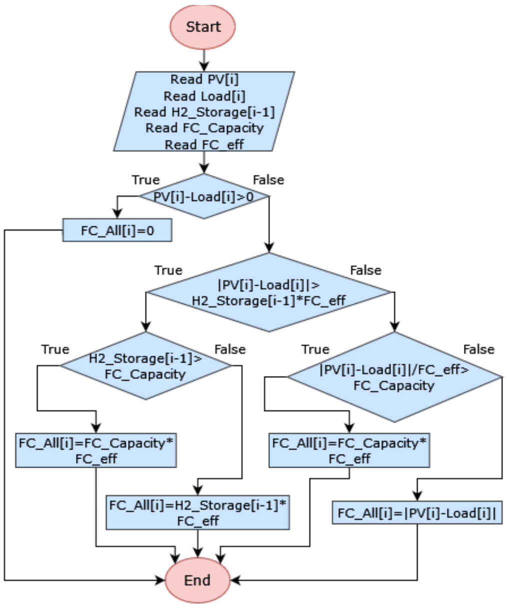

Fig. 10. FC allocation flowchart.

In Fig. 11, the battery contribution towards demand satisfaction is calculated.

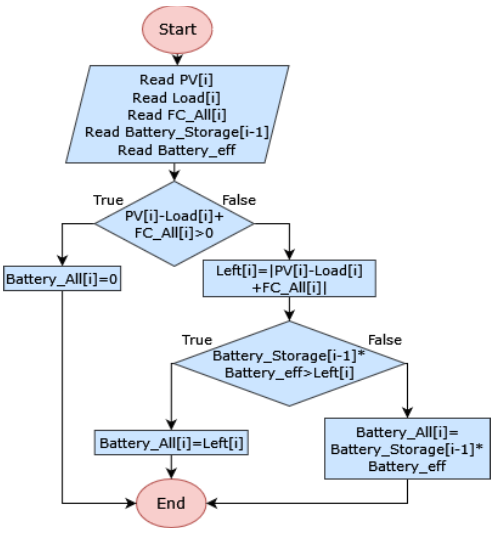

Fig. 11. Battery allocation flowchart.

If PV, fuel cell and storage capacity do not satisfy the load, then the grid's contribution is equal to:

$$Grid_{All.}=Load[i]-PV_{All.}[i]-FC_{All.}[i]-Battery_{All.}[i] \qquad (1)$$

In the next three figures, each component's losses are calculated. In Fig. 12 the battery losses are calculated for each hour's activation.

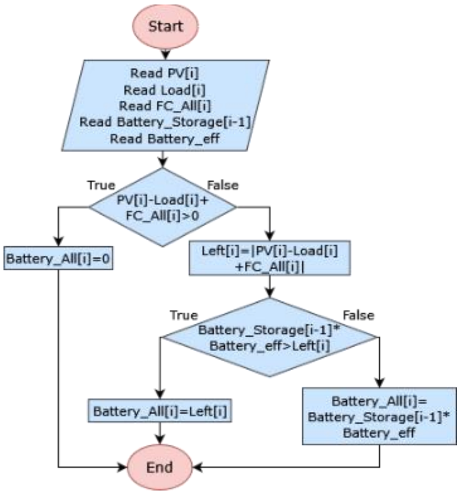

Fig. 12. Battery allocation flowchart.

In case of electrolyzer activation, the losses are calculated using (2):

$$Electrl._{loss.}[i]=Electrl.[i]*(1-Electrl._{eff.}-Electrl._{heat\ eff.}) \qquad (2)$$

Similarly, by using (3), fuel cell losses are accounted for.

$$FC_{losses}[i]=FC[i]*(1-FC_{efficiency}-FC_{heat\ efficiency}) \qquad (3)$$

In Fig. 13, the total rejections of the system are calculated. The rejections are equal to the surplus of RES production after consumption, successful storage and accounting of losses.

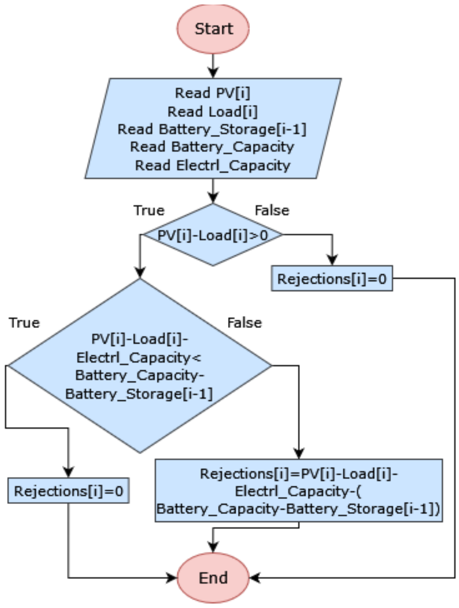

Fig. 13. Rejections flowchart.

In Fig. 14, the water tank's state of charge is calculated.

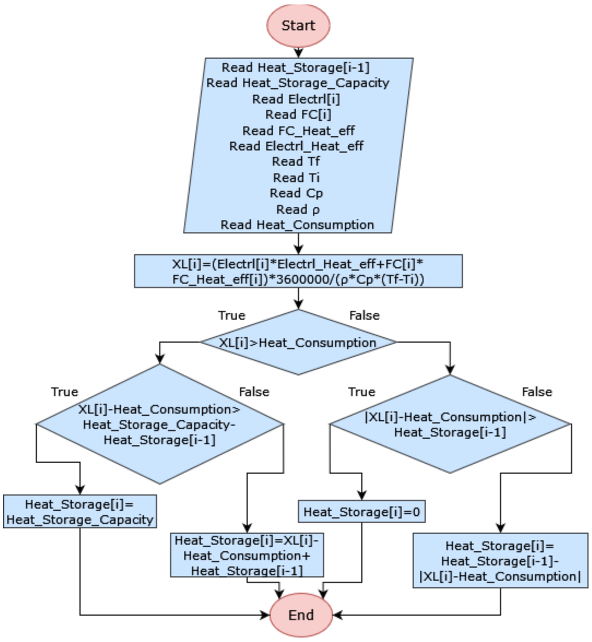

Fig. 14. Heat storage flowchart.

In Fig. 15 the contribution to water hourly consumption without the use of water heated with the heat exchanger is calculated.

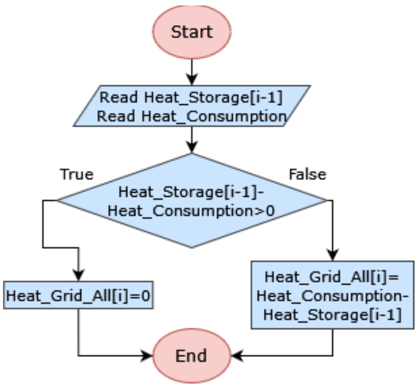

Fig. 15. Heat allocation from the grid flowchart.

Using Fig. 15 and the fixed rate of water consumption, the contribution of the water that is heated by the heat exchanger is calculated using (4):

$$Heat_{All.}[i]=Heat_{consumption}\text{-}Heat_{Grid\ All.}[i] \qquad (4)$$

In Fig. 16, heat rejections in case of power flow unable to raise the water's temperature above the specified upper limit are calculated.

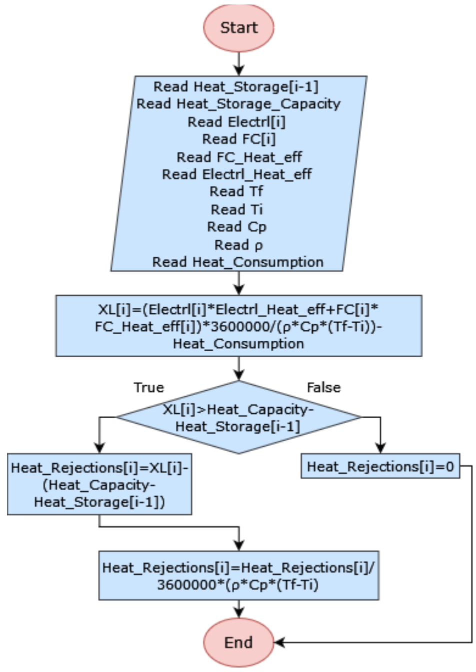

Fig. 16. Heat Rejections flowchart.

Using these values, overall metrics of the system are calculated and illustrate the overall efficiency of the system.

IV. Results And Discussion

The dashboard includes a timer, controlled by two buttons, "SET" and "START". When users activate the "SET" button, the application displays a message box, requesting input of integer, representing the consecutive hours of the simulation's duration. When users activate the "START" button the system iterates the hourly load data of the time range that is set. The features mentioned above are shown in Fig. 16.

Fig. 16. Timer and control buttons.

The system computes the variables described and visualizes the system's response for load satisfaction. The response is illustrated in Fig. 17 containing all the dashboard's charts.

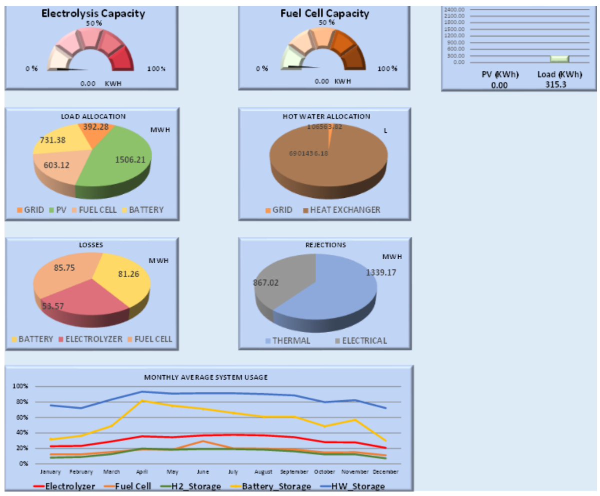

Fig. 17. Dashboard's visual charts.

The first two diagrams are speedometers, each one representing the current power input of the electrolyzer and FC in the current hour of the year. The third diagram represents a bar chart with the current value of load and PV production. The other four diagrams are pie charts and represent data equal to the average values of the illustrated values up to the current hour of the timer. The first pie chart visualizes the load allocation and depicts the contribution of each subsystem to the load. The second pie chart depicts the hot water allocation which is either satisfied from the water network or form the HE. The third and fourth pie charts show the system's rejections and losses. Finally, the last diagram shows the average percentage of capacity used for the whole year, providing an insight on the suitability of each component's installed capacity.

For the specific load time series, specific parameters in the control panel were set. A recent study has proven that the electrolyzer efficiency ranges between 60% and 80% for commercial use [10]. Depending on its type, FC efficiency ranges from 40-60% with polymer electrolyte membrane (PEM), Alkaline (AFC) and Solid Oxide (SOFC) FC being more efficient according to USA department of energy [11]. The energy efficiency for a lithium-ion battery (LIB) also heavily depends in its material structure, 90% being considered as a realistic efficiency [12]. Moreover, the heat energy that can be generated from the use of FC is about 20% of its output energy according to researchers in Malaysia [13]. An indicative thermal energy efficiency for both the electrolyzer and FC was set equal to 15%. The initial water temperature from the water network is set at 20°C, the upper limit equal to 40°C, while the water tank's capacity 15,000L and a consumption rate of 800 L/h.

For the specific settings, a simulation iterating the annual hourly values yields the results in Fig. 18.

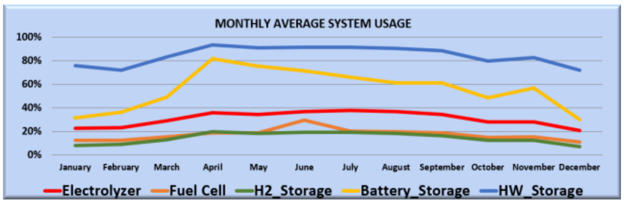

Fig. 18. Average rates of use for each month.

Fig. 18 leads to the conclusion that there is a minimal exploitation of the FC and hydrogen tank, in contrast to the heat exchanger subsystem's capabilities, with a large deviation of the conventional battery's subsystem rate of participation.

V. Conclusion

Technical training and education are crucial to a society's development and proper decision making. Simulating tools have proven to be effective in that regard, especially for complex subjects, such as state of the art RES technologies and their applications. In that context, a simulation software was developed using Microsoft Excel®, simulating a hybrid storage system coupled with a PV installation for load satisfaction. The user interface that was developed permitted ease of use, flexibility and detailed illustration of various metrics. Future research will focus on the establishment of similar dashboard tools, specifically for the emerging scenario of hydrogen valleys and microgrids.

Acknowledgment

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