Financial Assessment of Microgrid's Independence using RES and Hydrogen-Based Energy Storage

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Abstract: - The main difficulty that microgrids face is an economically feasible state of self-sustainability. The unpredictable behavior of dispersed Renewable Energy Sources (RES) and their stochasticity along with the usually high variability of electricity demand is a challenge for the stability of a microgrid. Therefore, innovative models for the development of energy systems that integrate new technologies in optimal and sustainable ways are required. Green hydrogen production is an emerging technology aiming to solve such problems through its use as a storage system within a viable business scheme. Integrating hydrogen production with RES and storage systems can enhance energy independence and economic opportunities. The focus of this paper is the proposal of a profitable financial scheme that leads to sufficient levels of the system's independence from a main grid. Such an approach is implemented by a cost-effective pathway for a microgrid located in Crete through the simulation and investigation of its system that achieves high levels of self-sufficiency by incorporating RES backed by hydrogen-based energy storage. The proposed methodology relies on assessing the system's sizing through the calculation of values that replicate its operation, with Net Present Value (NPV) serving as an indicator of the scheme's profitability. The financial evaluation of the investment predicts, under specific assumptions, a total initial cost equal to 12,037,150.00 EUR, and an NPV of 20 years equal to 2,489,862,897.40 EUR.

Key-Words: - RES Penetration, Green hydrogen, Hydrogen storage, Energy Storage, Electrolysis, Fuel Cell, Microgrids, Self-Sustainability.

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1 Introduction

The primary goal of a microgrid is to cover its electricity needs in a viable manner. A promising solution is the local generation of power, aiming for independence from the main grid. This shift is advantageous because the microgrid's financial stability can be affected by the grid's price fluctuations. When prices are low, buying electricity from a grid-connected provider is cost-effective, whereas local generation becomes more favorable when prices rise. To optimize the microgrid's performance in a rapidly changing energy market, the development of advanced control systems is essential.

RES can enhance a microgrid's independence by supplying locally produced, low-cost electricity, offering economically advantageous solutions. However, a significant drawback is the frequency instability that arises with a higher share of RES in the energy mix and the limited forecasting accuracy due to the unpredictable nature of RES production. Additionally, the restricted size of the microgrid's premises and the surrounding area may hinder the efficient installation of RES, making a desirable energy transition challenging.

A crucial component of a microgrid is its energy storage subsystem, which stores energy produced by RES during periods of low demand and discharges it when needed. However, installing traditional storage systems, such as lithium batteries, incurs high costs, making this investment impractical for small-scale microgrids or projects with limited resources. Hydrogen-based storage technologies offer both sustainable and cost-effective solutions.

Green hydrogen is produced through water electrolysis using electricity generated from renewable sources like wind and solar power. Various types of electrolyzers, such as alkaline electrolyzers (AEL), proton-exchange membrane electrolyzers (PEMEL), and anion-exchange membrane electrolyzers (AEMEL), can produce hydrogen in a gaseous state. These electrolyzers can be paired with a hydrogen storage tank and a fuel cell system to increase storage capacity and use the stored hydrogen gas as fuel for electricity generation. Beyond reducing carbon emissions, this design can be appropriately scaled to achieve energy independence, enhance grid stability, and provide financial benefits.

This study proposes a methodology for integrating a green hydrogen storage system into a microgrid located on the island of Crete. Along with the hydrogen system, its energy system uses RES, a diesel generator, and imported energy from the grid. The integration is designed to be profitable under specific assumptions, minimizing imported energy in a viable manner.

2 Literature Survey

2.1 Microgrid Energy Systems

Microgrids consist of small-scale energy generation systems and have distinct energy load profiles. Typically, they are low or medium-voltage distribution grids that rely on a combination of conventional fuel-consuming generators and RES. The reliability of energy generation can be enhanced by installing energy storage systems, which help address the irregular power output from photovoltaic (PV) and wind turbine (WT) systems, [1], [2]. Several studies have focused on optimizing energy systems at the local level. For instance, a comprehensive overview of recent advancements, methodologies, and future research directions in this field has been compiled, [3]. A multi-objective optimization model that minimizes energy consumption while supporting economic growth was also developed [4]. Similarly, a multi-objective optimization model for integrated energy systems, aiming to achieve both economic and environmental benefits through reduced carbon emissions has been implemented, [5]. To address the challenge of the intermittency of resources like wind and solar power, the optimization of RES was investigated, [6]. The proposed solution involves a strategic combination of diverse RES types and the integration of energy storage systems. The methodology employs a multi-pronged approach, thoroughly analyzing existing literature on optimal RES deployment.

2.2 Hydrogen Power and Storage Systems

In many cases, the optimal choice of an energy system, due to the stochasticity of RES plants combined with their dependence on climatic conditions and meteorological phenomena, is the hybrid energy system with a combination of at least one form of RES and storage with batteries and even diesel generators, [7]. Despite their benefits, microgrids present significant challenges, such as their isolation, the uncertain variability of RES plants, the stability of the electricity grid, and their economic and technical adequacy. Hydrogen production and storage as an energy carrier is a promising economic solution, especially in combination with RES infrastructure such as WT and PV farms. Several techniques for the production of 'green hydrogen' such as alkaline electrolysis (AEL), proton exchange membrane electrolysis (PEMEL), and anion exchange membrane electrolysis (AEMEL) are proposed in the literature.

Embedding any of the techniques in combination with fuel cells as an alternative electricity generator offers a viable prospect for improving the stability and independence of microgrids. A critical review of hydrogen storage systems focusing on the feasibility of this technology is provided while emphasizing the necessity to reduce costs to be commercially competitive, [8]. It also highlights the importance of hybrid systems combining hydrogen with short-term energy storage technologies and discusses the challenges related to low energy efficiency and high costs. The potential for economies-of-scale effects to reduce costs in the future is mentioned, but uncertainty prevails regarding their commercial attractiveness. The discussion of Japan's challenge with fossil fuel dependence after the earthquake and the proposal to develop and utilize renewable energy sources, underscoring the vulnerability of renewable energies and the proposed solution of hybridization with a storage system is summarized, [9]. The recent advances in hydrogen technology, including its application in transportation, industry, and power generation, as well as the challenges, barriers, and recommendations for the development of hydrogen technology and environmentally friendly smart energy systems in Vietnam are discussed, [10].

Energy management in a microgrid encompasses a sophisticated computerized framework targeted primarily at providing optimized resource planning, [11]. It uses modern computer technology to boost the operation of distributed energy sources and energy storage systems, [12].

This paper aims to optimize the sizing of a microgrid's RES and hydrogen system to achieve independence and profitability. Unlike other publications, this study employs a detailed simulation algorithm that performs hourly calculations of storage state of charge and power allocation. The algorithms are designed to be flexible, allowing for the customization of installed capacities and overall system properties, such as generator lower and upper limits, interconnection capacity, prices, etc. This adaptability enables a financial evaluation of specific systems based on distinct energy profiles and photovoltaic production.

3 Methodology

The proposed installation entails the incorporation of RES production, comprising photovoltaic (PV) installations, a pre-installed diesel generator system, and the implementation of a hydrogen system. The methodology is structured to accommodate input data related to the system's operation, including annual load hourly data ranging up to a few hundred kW, normalized hourly data from a solar farm on the island of Crete, and parameters related to the operation and costs of each component's installment and operation.

The microgrid's design prioritizes the system's independence from the main grid to which it is connected. Both in load satisfaction and handling of power produced locally by RES, the local production strives to maintain the majority of power contribution to the system's demand and its financial profitability, while the connection to the grid serves as a reserve or complimentary source of income. The microgrid's independence relies on the usage of solar panels, fuel-consuming generators, and a hydrogen-based storage system coupled with a fuel cell subsystem. The microgrid's design is shown in Figure 1.

For the study, the proposed energy demand response sequence takes into account the following stages:

The sequence commences by activating the minimum essential load from conventional units. This ensures stable operation while minimizing reliance on conventional fuels. Following minimum conventional generation, available energy from RES that is produced locally is utilized to directly supply the grid. If real-time RES production is insufficient to meet the remaining demand, the strategy incorporates the use of stored energy.

The energy system aims to capture the remainder of RES production and store it in a tank in the form of compressed hydrogen gas. The conversion is realized through the electrolysis of water, powered by the energy to be stored. The purpose of the proposed storage method is to be used to address the deficiency of the RES system in case of reduced weather potential through the conversion of the compressed gas into electricity with the use of a fuel cell system integrated into the overall hydrogen subsystem. However, the combined contribution of RES-hydrogen coupling may not suffice for the hourly electricity demand. In such a case, the diesel generator subsystem's operation can be proportionally increased up to its maximum technical limits or until the hourly load is satisfied. If all previous measures are inadequate to meet demand, controlled electricity import stemming from the external grid can be implemented as a last resort. The specified priority chain is summarized in Figure 2.

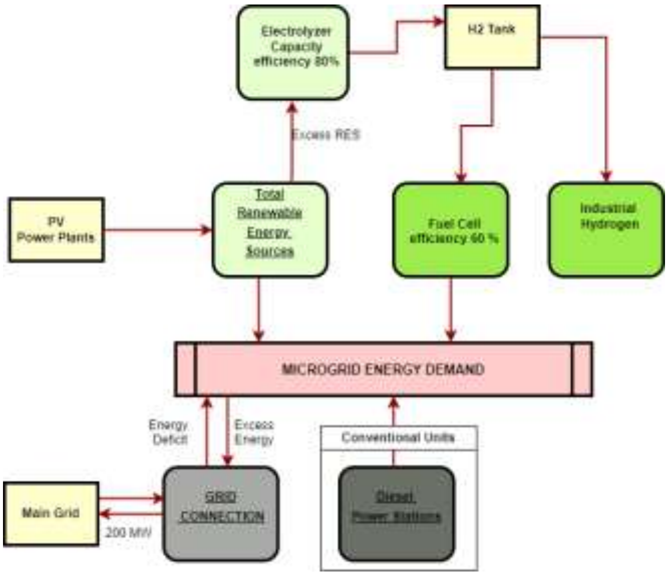

Fig. 1: Illustration of the microgrid's design

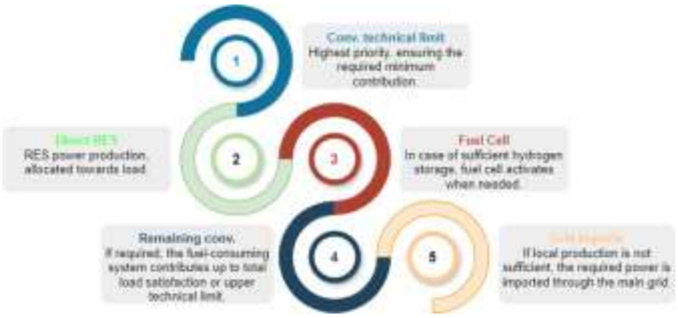

Fig. 2: Load satisfaction's hourly priority design

An alternative process chain is activated to capitalize on the excess RES production, in case of demand satisfaction from the generator system’s lower limit and current hourly RES energy. First, any surplus is prioritized for conversion into hydrogen and storage in available hydrogen tanks, adopting the efficiency of the electrolysis process equal to 60%, [13]. After excluding the electrolyzed energy and accounting for the associated losses, the remaining available energy is allocated for export to the main grid. This export is limited to 200kW, as a hypothetical limit determined by the supplier and microgrid representatives, and adheres to technical limitations to ensure grid stability. If a surplus of RES energy remains even after storage and export, the design proposes its sale through hydrogen production, mainly for industrial use, up to the electrolysis system’s remaining availability of the total capacity. The remainder of the production is rejected from the system. The specific power flow produced by RES is depicted in Figure 3.

Fig. 3: Power flow of RES hourly production

For this particular analysis, the annual demand and production are assumed to remain constant, leading to consistent annual cashflows, except for the replacement cost of the electrolysis and fuel cell subsystems in the 10th year. The hourly simulation of the energy system is conducted using the flowcharts outlined below.

Direct RES is the RES hourly production contributing directly to load satisfaction, calculated in Figure 4 (Appendix).

The computation of the storage subsystem’s state of charge is divided into separate flowcharts, Figure 5 and Figure 6 in Appendix, describing the instances of charge and discharge respectively.

If the stored quantity of compressed gas is sufficient, the energy produced by the fuel cell subsystem in each hour of the simulation is described in Figure 7 (Appendix).

The quantity of excess energy effectively stored in the hydrogen tank, after losses, for every hour is computed in Figure 8 (Appendix).

The total hourly contribution of the diesel generator system for each hour T (TOTAL CONV.) is calculated in Figure 9 (Appendix).

The import of energy required to satisfy the remaining demand is calculated in Figure 10 (Appendix).

The amount of excess energy sold to the national grid shall be determined by the processes in Figure 11 and Figure 12 in Appendix.

If, by the end of the electrolysis storage stage, the electrolyzed energy has not reached the subsystem’s nominal value, the remaining energy after export allocation is used to produce green hydrogen for industrial sector trade, contributing to the system's profitability. The produced amount is calculated in Figure 13 (Appendix).

To estimate the relevant income, the hydrogen mass (in kg) produced during the process of Figure 13 (Appendix) was calculated using the lower heating value of hydrogen (LHV H_2) equal to 33.33kWh/kg. The produced hydrogen mass to be compressed for sale is calculated:

$$\text{Mass}_{\text{H2}}=\frac{\text{Electricity used*Electrol. Eff.}}{\text{LHV H}_2} \tag{1}$$

Due to the limited efficiency of the hydrogen system's components, some energy is lost during allocation to and from these components, mainly due to heat conversions. These losses are accounted for by following the process outlined in the chart shown in Figure 14 (Appendix).

The estimated rejected the power of the system for each hour of operation is achieved through the flowchart described in Figure 15 (Appendix).

To approximate the amount of diesel fuel required for the operation of the conventional system, [14] was referred to, utilizing the value of 34% efficiency for all hours for simplicity.

All relevant costs and prices necessary for calculating the NPV are compiled in Table 1. Most prices correspond to contemporary market data; thus, the methodology can yield results suitable for decision-making applied to the current market structure. The interconnection price is equal to the agreed-upon price for both the imported power to the microgrid and the exported power to the grid, stemming from local RES production. Since the specific scenario under investigation concerns the location of Crete, the hydrogen selling price was calibrated to be equal to the optimal price for a hypothetical hydrogen production facility situated on the island of Crete, per the study examined in [15].

Table 1. Types of investment costs

Type of expense	Cost
Interconnection price	0.18 EUR/kWh
Hydrogen gas price	3.5 EUR/kg
H2 Tank Installation Cost	6.0 EUR/kWh
PV Installation Cost	600.0 EUR/kW
WT Installation Cost	1,000 EUR/kW
Electrolyzer Installation Cost	1,500 EUR/kW
Fuel Cell Installation Cost	1,500 EUR/kW
Compressor Installation Cost	50.0 EUR/kW
Inverter Installation Cost	100.0 EUR/kW
RES O&M cost rate	5%
Total O&M cost rate	2%
Diesel Price	2.00 EUR/lt
Annual Discount Rate	3.0%

The total lifetime of the investment is 20 years, equal to the estimated lifetime of the PV installation. The durability of both the electrolyzer and the fuel cell subsystems is considered equal to 10 years. For the specific simulation, the decision variables are the PV installed capacity (in kW) and the hydrogen tank's storage capacity (in kWh), since the electrolyzer and fuel cell's capacity were calibrated equal to the PV capacity, to achieve theoretically total RES utilization. The diesel generator's lower limit was set to the minimum value of the load time series, while the upper limit was 20% higher than the lower, permitting ample RES penetration to the energy mix.

The NPV was calculated using:

$$\mathrm{NPV}=\sum_{t=0}^{L}\frac{\mathrm{Cashflows(t)}}{(1+r)^{t}}-\mathrm{CAPEX} \tag{2}$$

Where L is the investment's lifetime, Cashflows(t) represent the income and expenses of the business during the year t, and CAPEX is the initial expenditure.

The CAPEX includes the expenses for the PV installation and its inverter, along with the hydrogen subsystem. These costs encompass the installation of the water electrolysis system at its nominal capacity, the fuel cell system at its nominal power, the hydrogen storage compressor, the tank's total energy capacity, and the inverter connected to the fuel cell for current conversion.

The total income generated by the proposed installation is calculated as the sum of the products of the exported energy quantity and hydrogen mass (in metric tonnes) by their respective prices. On the other hand, negative cash flows encompass expenses such as grid import costs, diesel costs for conventional system operation, total operational and maintenance expenses of the RES system (estimated as an annual percentage of the installation cost), and likewise, operational and maintenance costs of the hydrogen system.

For the calculation of the NPV, the discount rate for the calculation of the future income in present value is crucial. In the specific scenario, its value is assumed to be equal to 3%.

4 Results

For a wide range of the two decision variables, the graph of NPV values is drawn, depicted in Figure 16.

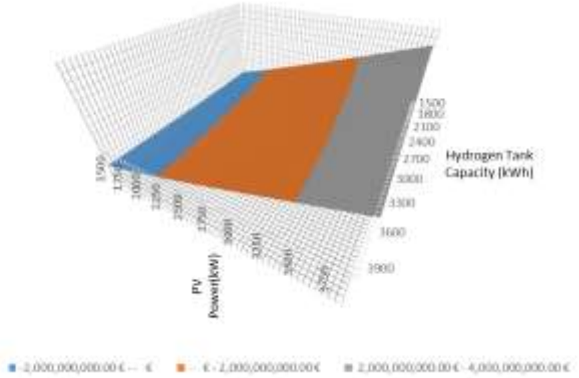

Fig. 16: NPV with respect to PV power and Hydrogen tank storage

Negative NPV values imply net loss for the investment, while positive values exhibit profit for the period of the investment. The NPV does not converge to a specific value, due to the assumption that the microgrid can sell the entirety of each hour's industrial hydrogen production. In this context, the optimal solution is the set of independent variables that yield the maximum NPV, with minimal CAPEX and at least 90% annual self-sufficiency. The approach employed was brute force, commencing from values resulting in nearly zero NPV, persisting until the criteria were met and the maximum NPV was attained. The identified set is 3100kW of PV installed power and 1500 kWh hydrogen tank capacity.

The annual energy mix determined by the solution is shown in Figure 17.

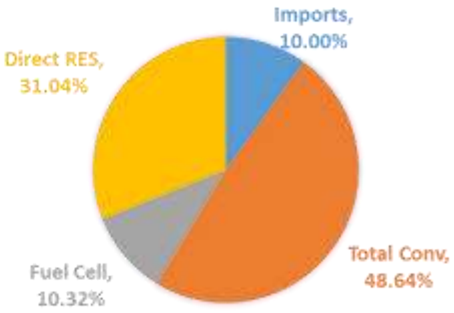

Fig. 17: Load satisfaction’s hourly priority design

A little less than half of the total energy arises from the diesel generator system, meaning a heavy dependence on the specific technology and a considerable impact of diesel price fluctuations on the microgrid’s logistics. As required, the imports are limited to 10% of load satisfaction, while the fuel cell increases RES penetration by 10.32%. The daily energy mix for an entire simulated year is shown in Figure 18.

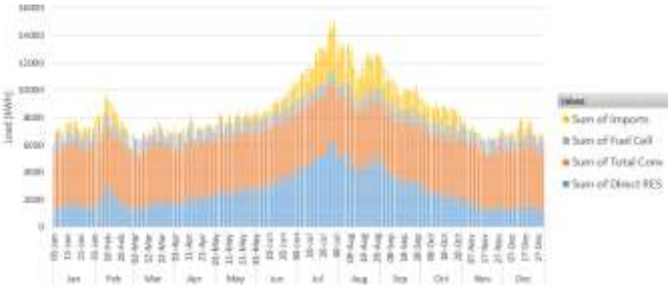

Fig. 18: Load daily mix

For the specific energy profile, the vast majority of imports are met during the summer period when the load demand is at its peak and local production is insufficient to cover it.

In Figure 19, the annual RES production and its allocation are depicted.

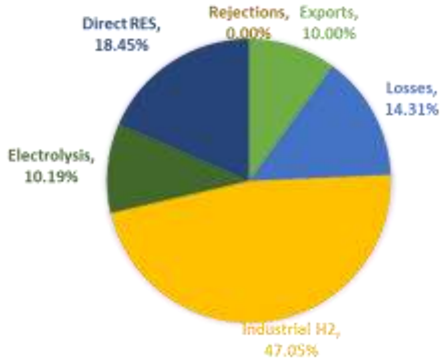

Fig. 19: Annual microgrid’s RES production

The vast majority of the produced energy is converted to hydrogen for sale, explaining the high value of NPV. The rejections of the system are zero, attributed to the costly, yet profitable high installed capacity of the electrolysis subsystem. The above can be observed on a daily scale in Figure 20.

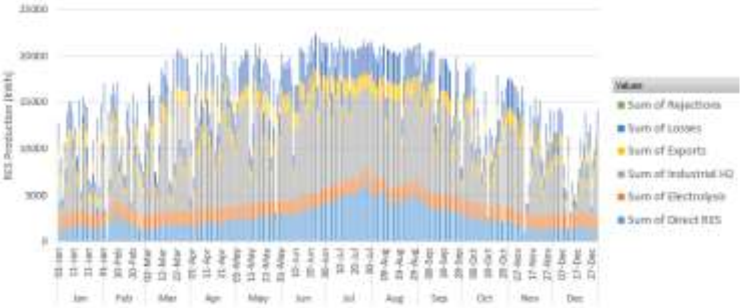

Fig. 20: Load satisfaction’s hourly priority design

The RES production reaches its peak during the summer, characterized by minimal day-to-day variations. In contrast, the winter months exhibit substantial daily fluctuations in total RES production. This is unlike the energy mix shown in Figure 18, where all contributors display more consistent output patterns.

The resulting CAPEX is calculated equal to 12,037,150.00 EUR. In Figure 21, the CAPEX attributed to RES and the hydrogen system is depicted.

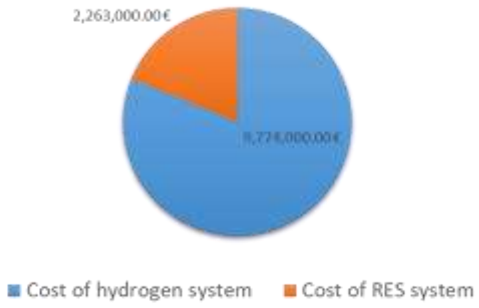

Fig. 21: CAPEX breakdown

The vast majority of expenses concern the hydrogen system, the main obstacle in hydrogen-based energy investments. At the same time, the hydrogen system is the main contributor to the microgrid’s income, while the fuel purchases are the costliest annual expense, as can be seen in Figure 22.

The NPV is equal to 2,489,862,897.40 EUR, a substantial value attributed to the assumption that the entirety of the hydrogen produced for sale to the industrial sector can be sold. A more realistic simulation, reserved for future endeavors, should include additional constraints regarding the market’s demand and general status regarding hydrogen transactions. The market's landscape regarding taxation upon produced hydrogen, current demand, and competitive prices would make such a simulation more realistic by limiting the traded hydrogen gas and introducing another layer to the optimization problem.

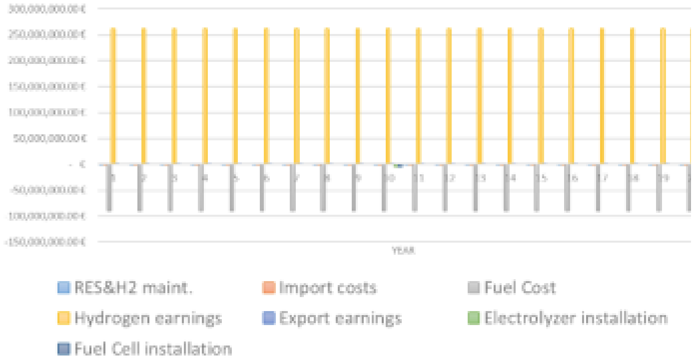

Fig. 22: Annual cashflows

5 Conclusion

This paper investigates a proposed business strategy aimed at attaining self-sufficiency in meeting the energy demands of a microgrid. The suggested enhancements to an existing energy system, initially reliant solely on a diesel generator, involve integrating RES through photovoltaic technology and implementing energy storage using green hydrogen produced via electrolysis. This hydrogen can be utilized both as a commodity and as fuel for additional electricity generation. The evaluation of this scheme's financial viability employs the NPV metric. The methodology successfully identifies decision variables within the model regarding the sizing of the RES and hydrogen subsystems to be installed. The solution results in a positive NPV of 2,489,862,897.40 EUR over 20 years. It achieves 90% self-sufficiency and a 41.36% contribution from RES, optimizing the utilization rate of the PV system and significantly reducing diesel costs. Consequently, this leads to a substantial increase in the estimated profits. The findings of the methodology should be interpreted considering the assumptions of unlimited hydrogen demand and the absence of restrictive policies that could impose taxation schemes or limitations on the production of hydrogen gas.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work the authors used Grammarly in order to improve the clarity of text and minimize grammatical errors. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed to the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare.

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APPENDIX

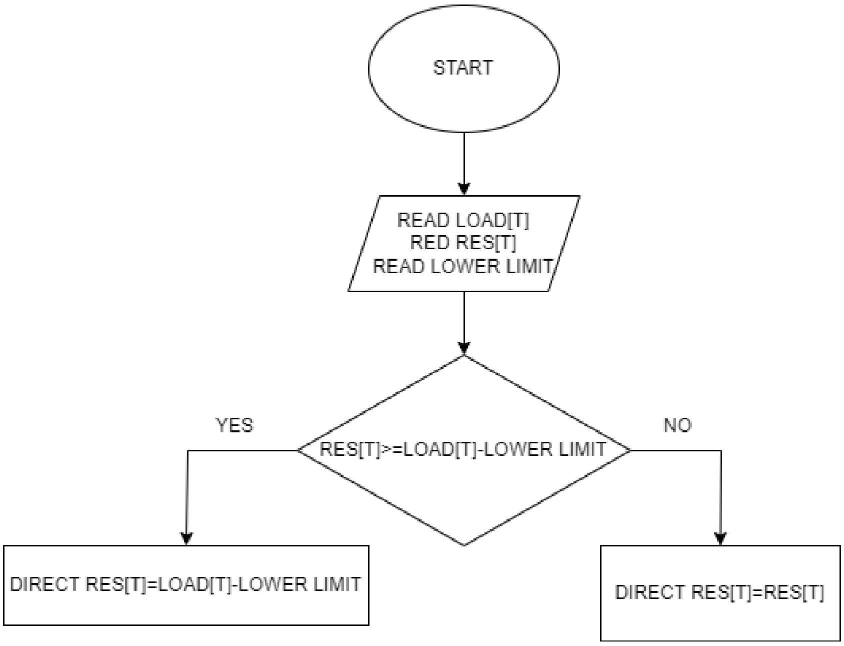

Fig. 4: Direct RES calculation

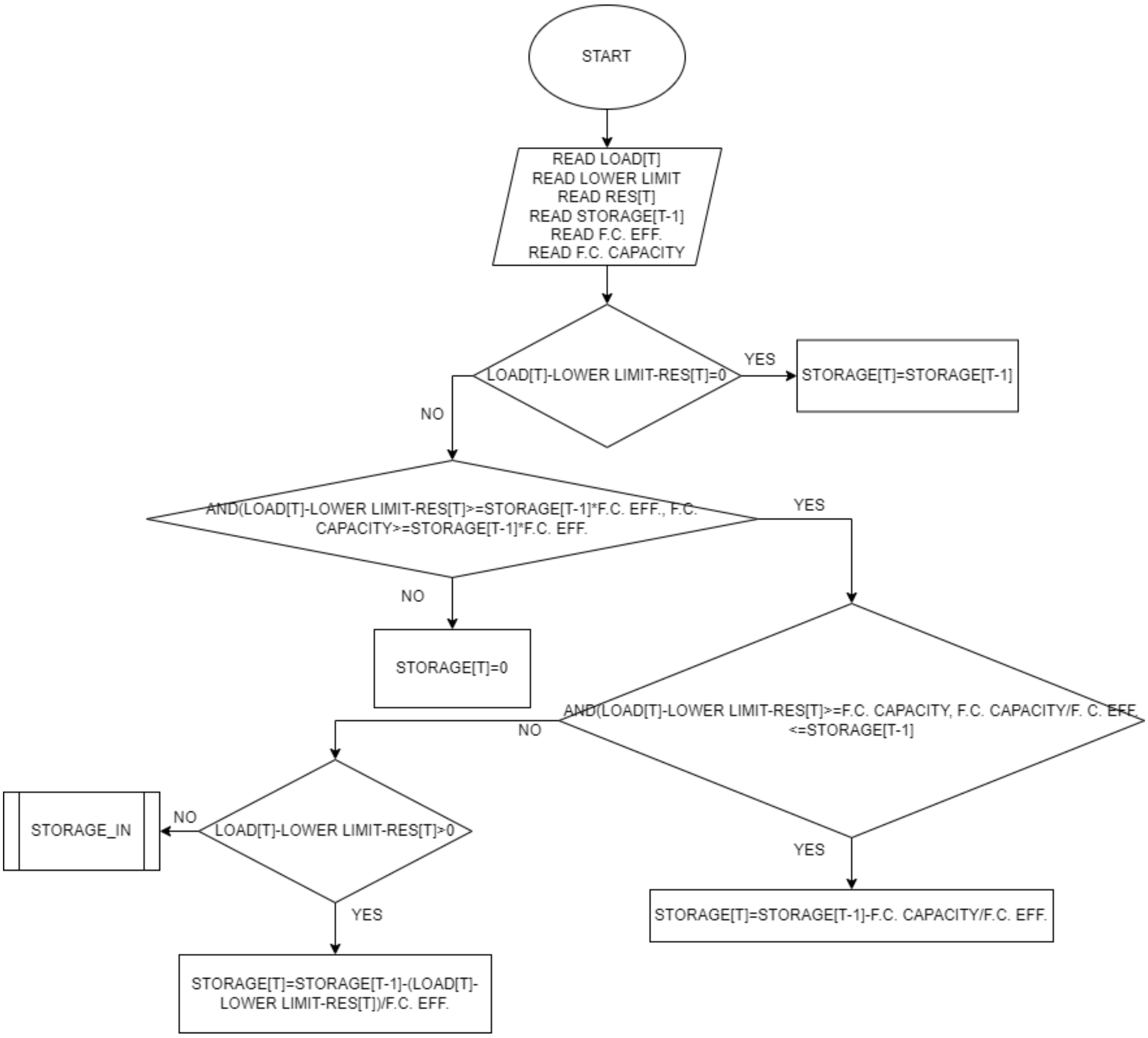

Fig. 5: Hydrogen tank’s charge level after discharge activation

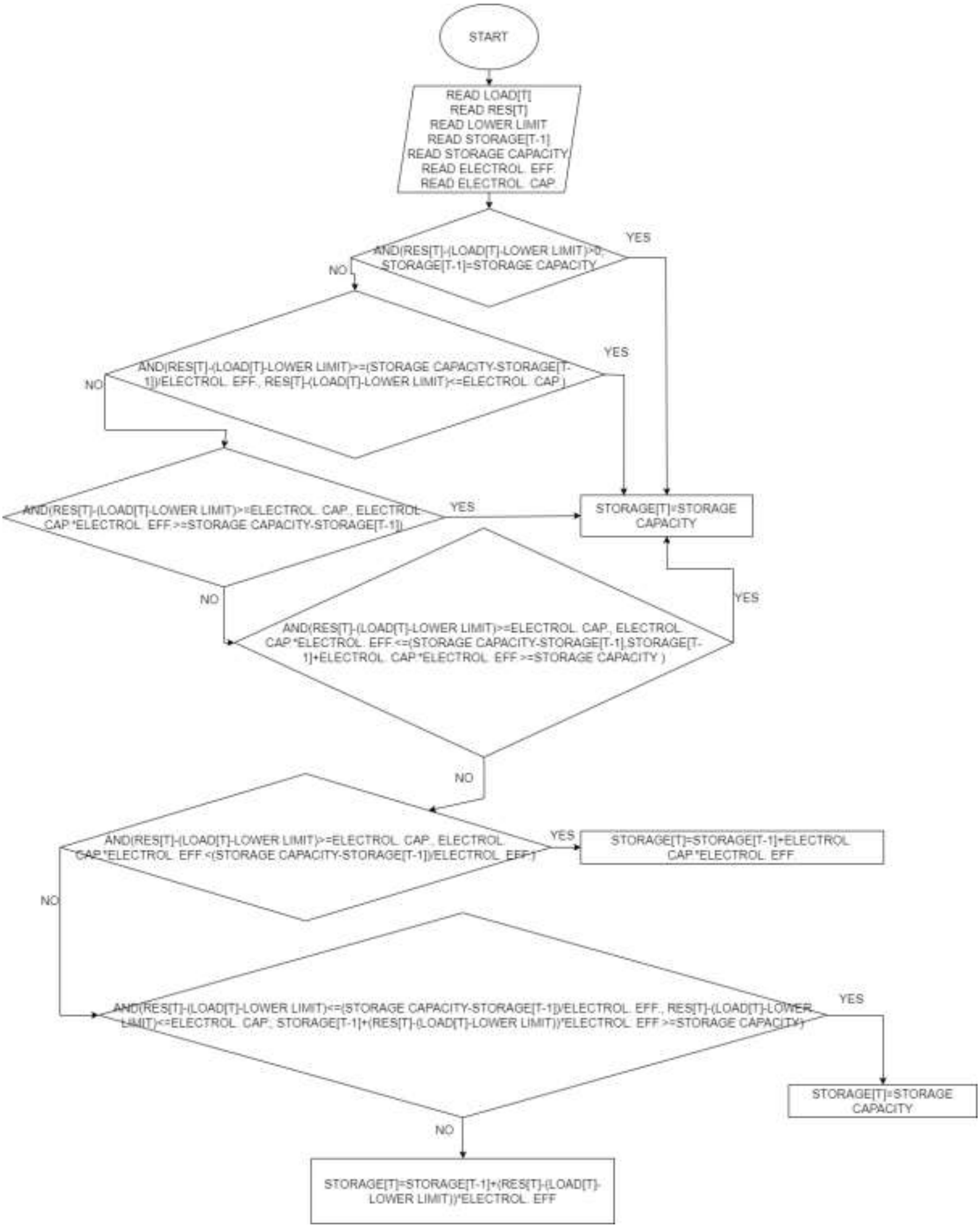

Fig. 6: Hydrogen storage state of charge after electrolysis process

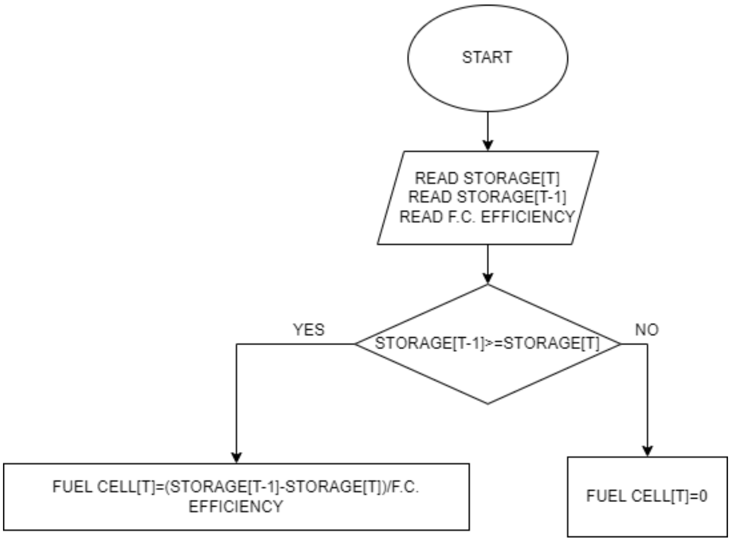

Fig. 7: Fuel Cell's contribution for each hour T

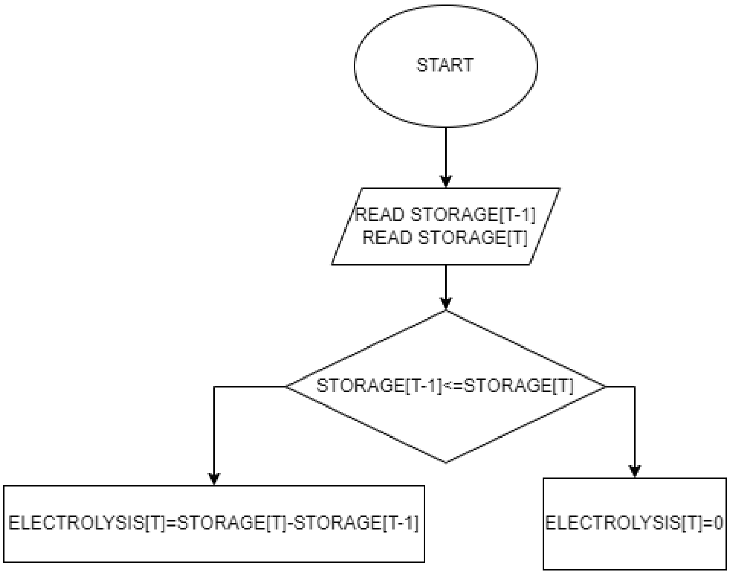

Fig. 8: Hourly Electrolysis production

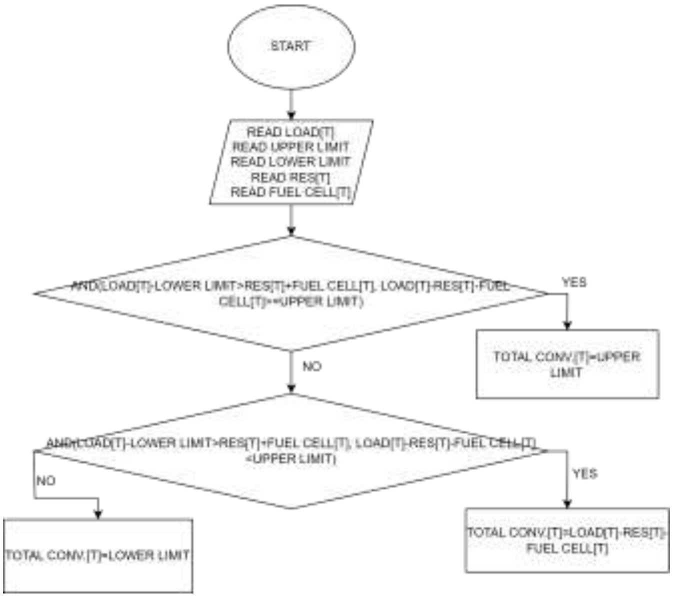

Fig. 9: Conventional system's hourly contribution

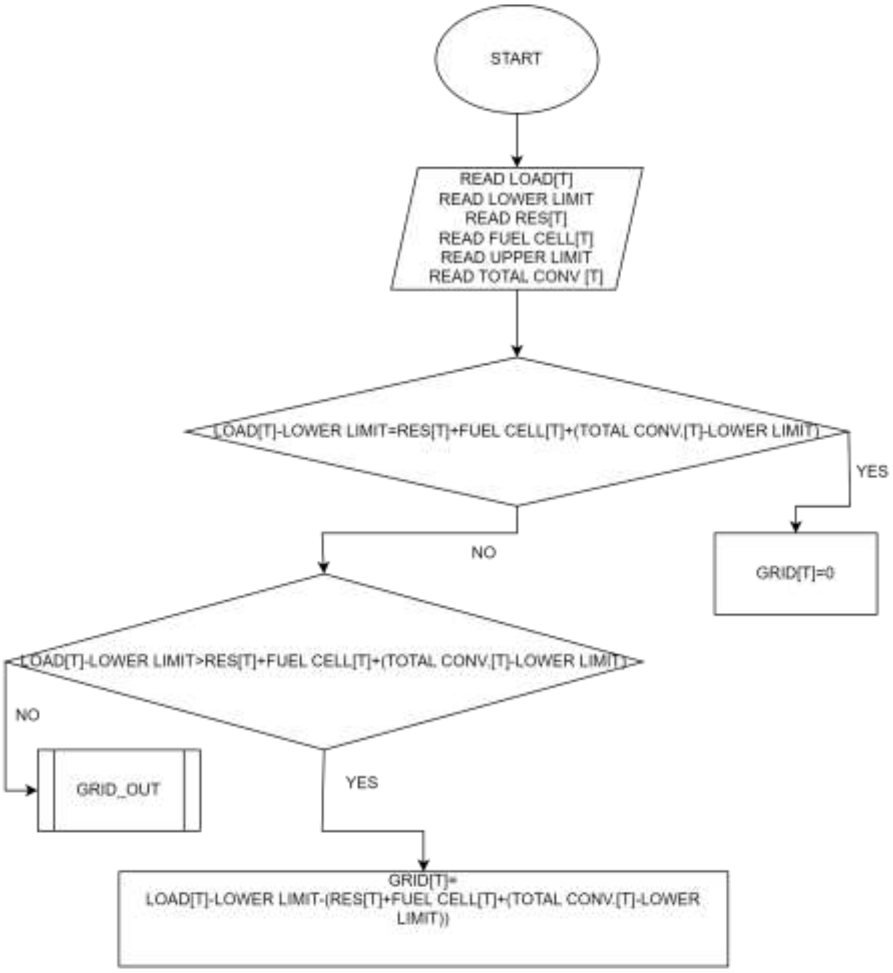

Fig. 10: Imports from the grid

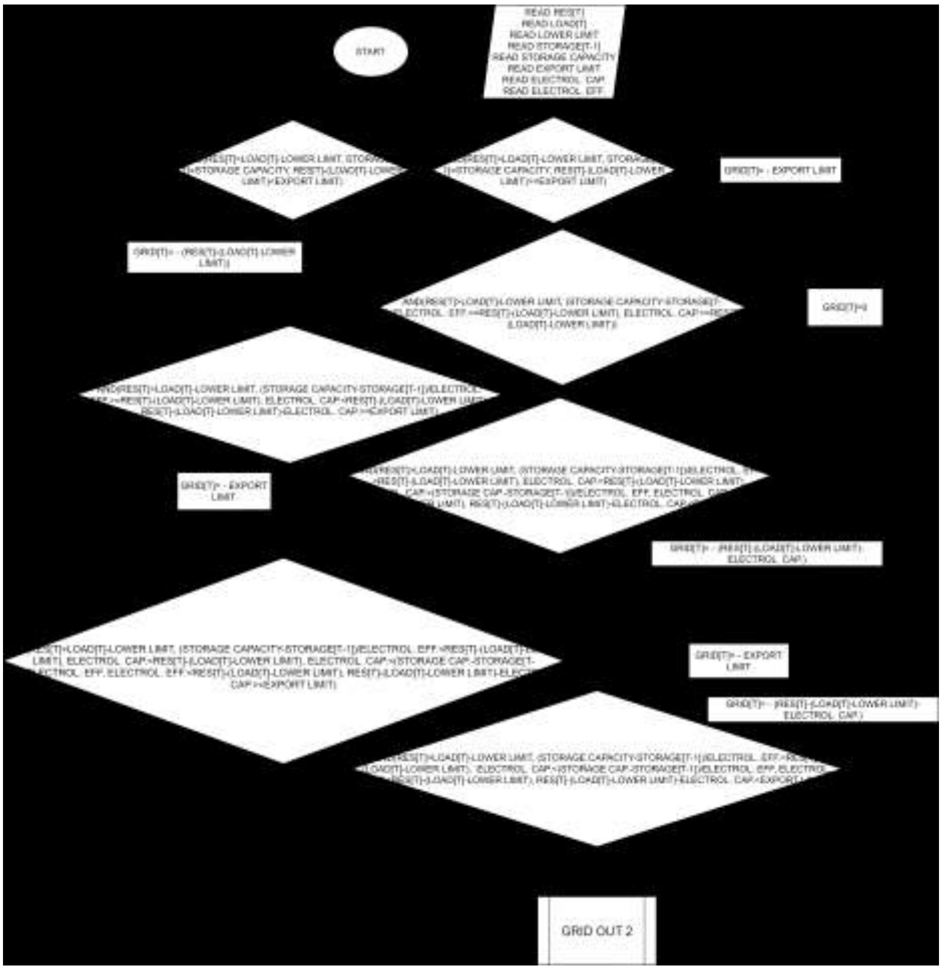

Fig. 11: Power exported to the grid (part 1)

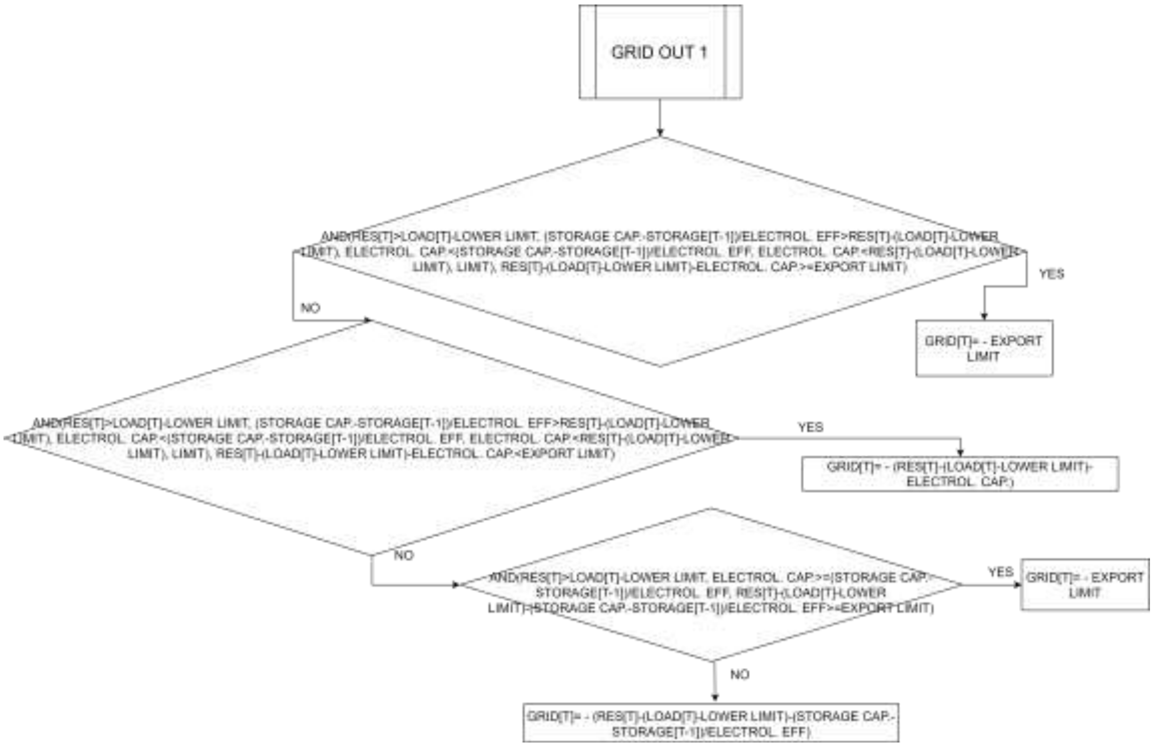

Fig. 12: Power exported to the grid (part 2)

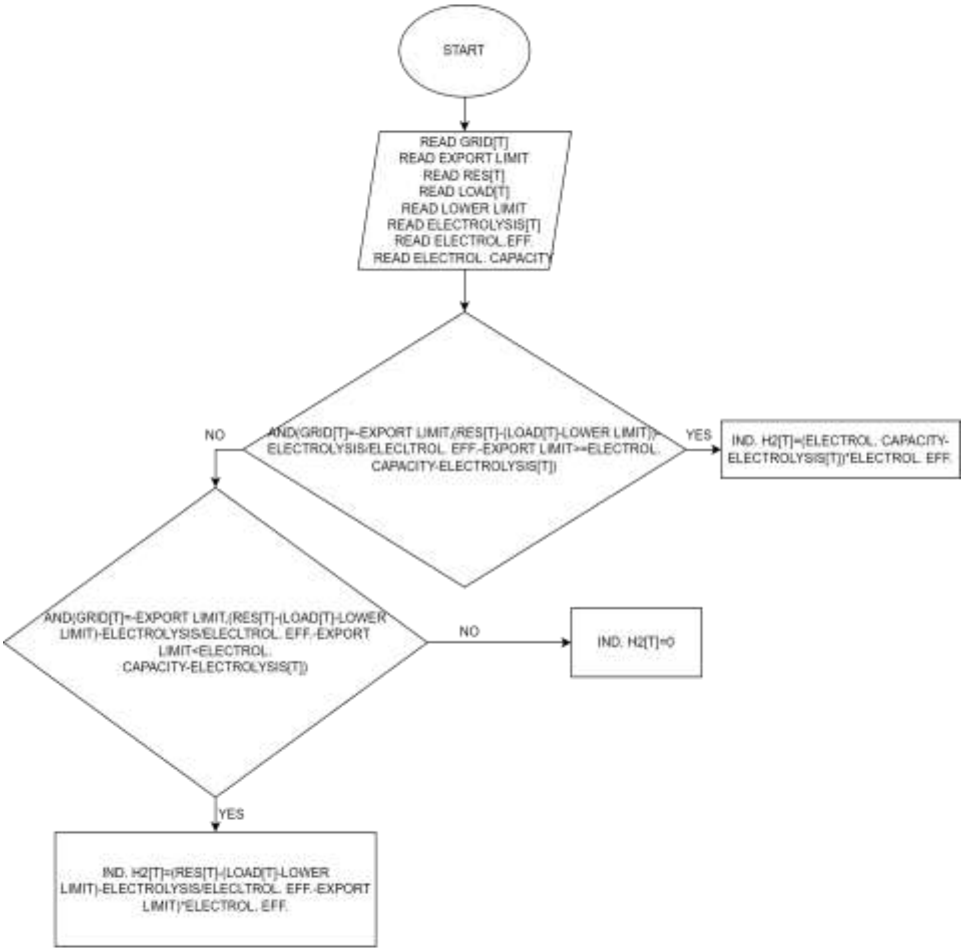

Fig. 13: Industrial hydrogen produced in energy units

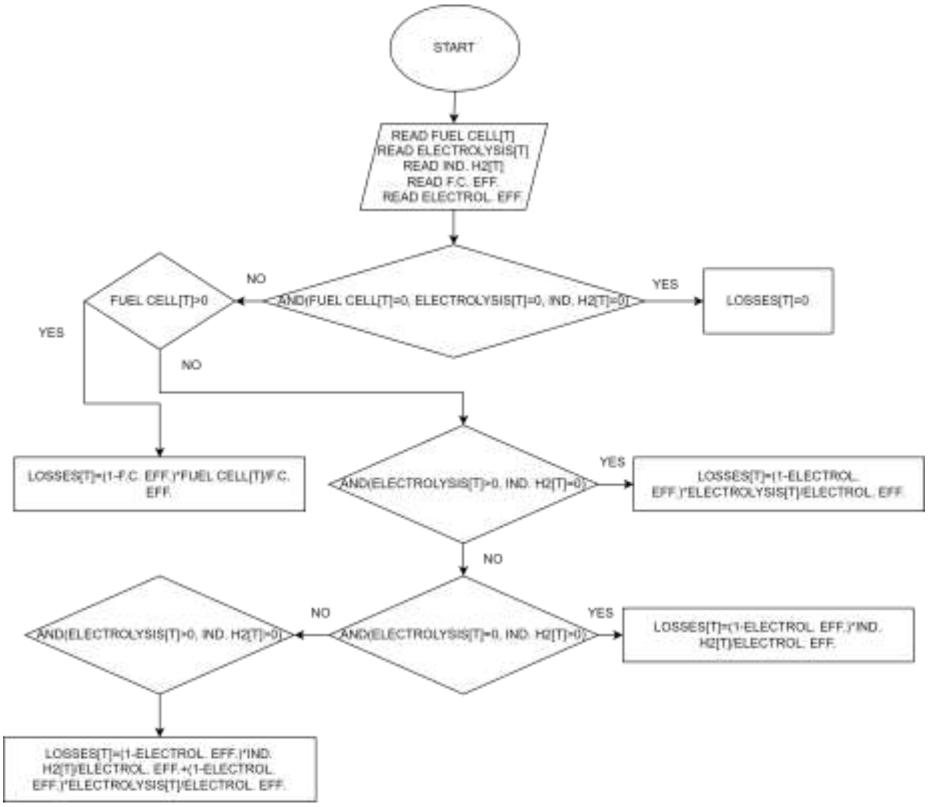

Fig. 14: Hourly microgrid’s losses

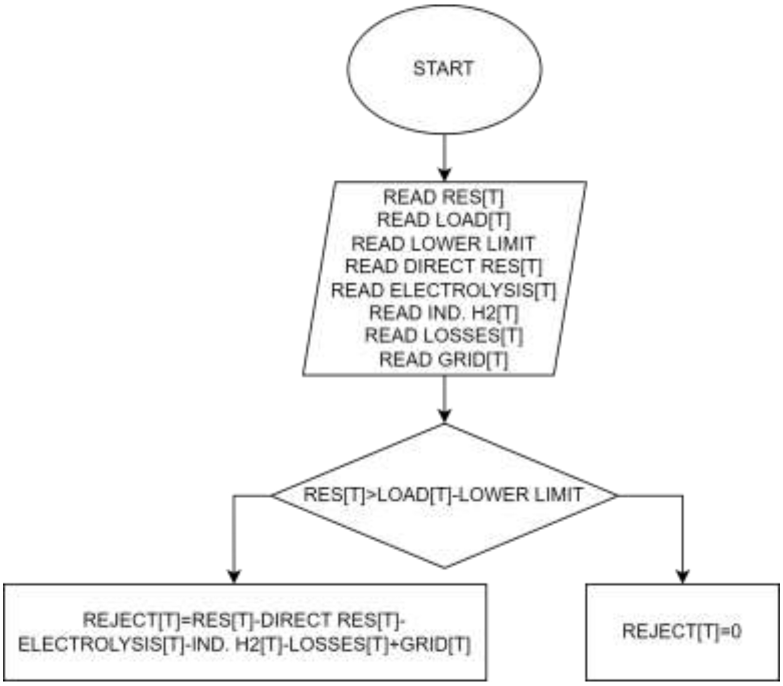

Fig. 15: Hourly rejections of the system