Hydrogen Microgrid: Notes and Physical Model

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1 Introduction

The H2GLASS project focuses on the production of hydrogen in order to substitute the natural gas as a fuel for a glass furnace. The electrolyser considered for this purpose is a Polymer Electrolyte Membrane (PEM).

The power supply of the electrolyser comes from electrical grid and PV generation. The electrolyser is directly connected to the burner, without considering any storage system. The power load is considered constant for the all year. All the hydrogen produced is instantaneously burned in the furnace

2 Industrial Process for the glass production

2.1 Glass production

The raw materials involved are silica sand or ground-up waste glass called "cullet". The following steps resume the passages for the industrial production:

1. the preparation of mix of ingredients: in a batch formers, fluxes, stabilizers and colorants are added in order to mix the attended glass combination. The batch mixer accounts for the greatest share of electricity use in this step, while batch accounts for 4%.

2. the melting stage: the batch is fed into the furnace. This passage represents half of the energy use in glass production. For this purpose natural gas or fuel oil are involved.

3. the conditioning: after the melting and refining, the glass can be formed through a continuous shaping process for float glass or fiberglass or in portions called "gobs" to make container glass. In this phase, natural gas is used for heating, while electricity is used for conveyors, fans and mechanical pressing.

The information above are considered from: [6].

2.2 Consumption

As said previously, the energy consumption is related to the high temperature that are related and maintained during the steps of the processes. The temperatures characterizing are resumed in Table 1.

The batch plants are fed by 100% electricity for bucket elevators, pneumatic conveyors or batch mixers. It accounts for minor share of a glass plant's total energy demand equal to 4%.

The melting process requires between 50 and 85 % of the total energy where the reached temperature belongs to the range 1200 - 1600 °C. The quality of the glass is related to the residence time of the batch mixture. In Germany the residence time can vary between 5 and 24 h, with an average value of 12 h.

Phase	**Temperature [°C]**
Batching and Preparation	15 - 325 °C
Melting and Fining	1200 - 1600 °C
Forming	600- 1200
Post-Forming and Finishing	100- 600

Table 1: Phases and corresponding temperature ranges

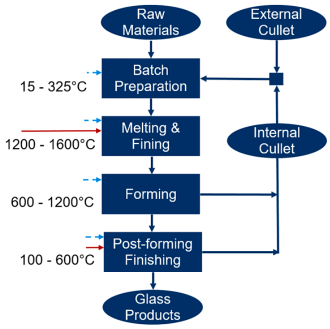

Figure 1: Explanation of the overall process temperatures for each step of the glass production process

The Figure 1 resume in a diagram the data reported in this paragraph.
The information above are considered from: [2]

2.3 Model 4

The Figure 2 shows the plant of this model. In this section we consider that the electrolyser is fed by the grid and PV generation. The tank with the compressor are inserted between the Node 2 and Node 3. An hydrogen bottle tank is added at node 3.

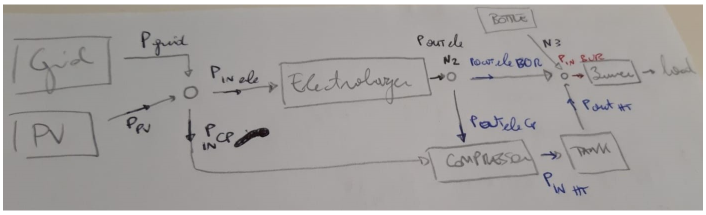

Figure 2: Model 4 considering electrolyser, compressor, tank, bottle tank and burner

The power balance at Node 1:

$$P_{grid}(t) + P_{PV}(t) = P_{INele}(t) + P_{INCP}(t) \tag{1}$$

The $P_{grid}(t)$ is the withdrawal power from the grid, considered as a sizing variable.

The definition of the PV generation:

$$P_{PV}(t) \leq G_{PV} \cdot F(t) \tag{2}$$

where G_{PV} is the rated PV installed capacity and $F(t)$ is the PV power forecast. The PV installed capacity is considered as sizing variable in the optimization function.

The conditions at the electrolyser:

$$P_{OUTele}(t) = \eta_{ele} \cdot P_{INele}(t) \tag{3}$$

where η_{ele} is considered around 80%.

$$P_{INele} \leq \lambda_{MAXele} \cdot P_{RATEDele} \tag{4}$$

$$P_{INele} \geq \lambda_{MINele} \cdot P_{RATEDele} \tag{5}$$

where $P_{RATEDele}$ is the rated power at 1MW.

The power balance at Node 2:

$$P_{OUTele}(t) = P_{INHT}(t) + P_{OUTeleGB}(t) \tag{6}$$

The conditions at the Hydrogen Tank:

$$P_{INHT}(t) = \frac{P_{OUTele}(t) \cdot l_{CP}}{LHV_{H2}} \tag{7}$$

where l_{CP} is the compression specific work and LHV_{H2} is the Lower Heating Value of hydrogen.

$$P_{OUTeleCP}(t) = P_{INHT}(t) \tag{8}$$

The conditions at the Hydrogen Tank:

$$E_{HT}(t) = E_{HT}(t-1) + P_{INHT}(t) \cdot \Delta t - P_{OUTHT}(t) \cdot \Delta t \tag{9}$$

$$E_{HT}(t_{in}) = LOH_{in} \cdot E_{RATED} \tag{10}$$

$$E_{HT} \leq LOH_{MAX} \cdot E_{RATED} \tag{11}$$

$$E_{HT} \geq LOH_{MIN} \cdot E_{RATED} \tag{12}$$

where LOH_{in} is the Level Of Hydrogen of the storage tank at the initial condition, LOH_{MAX} is the maximum value and LOH_{MIN} is the minimum one.

The conditions at the Hydrogen Bottle Tank:

$$E_{bo}(t) = E_{bo}(t-1) - P_{OUTbo}(t) \cdot \Delta t \tag{13}$$

$$E_{bo}(t_{in}) = E_{RATEDbo} \tag{14}$$

where $E_{RATEDbo}$ is the rated capacity of the bottle tank injecting hydrogen at node 3.

The power balance at Node 3:

$$P_{OUTeleGB}(t) + P_{OUTHT}(t) + P_{OUTbo}(t) = P_{INbur}(t) \tag{15}$$

The conditions at the burner:

$$P_{OUTbur}(t) = \eta_{bur} \cdot P_{INbur}(t) \tag{16}$$

where η_{bur} is considered at 100%.

$$P_{INbur} \leq \lambda_{MAXbur} \cdot P_{RATEDbur} \tag{17}$$

$$P_{INbur} \geq \lambda_{MINbur} \cdot P_{RATEDbur} \tag{18}$$

where $P_{RATEDbur}$ is the rated power at 1MW (general value).

The conditions at the load:

$$P_{OUTbur}(t) = P_{load}(t) \tag{19}$$

The thermal load at the furnace follows a behaviour of a random function, where the values are included between 20 and 80 MW. The Figure 3 represents the evolution along the week, while the Figure ?? shows the evolution of the load along the entire year.

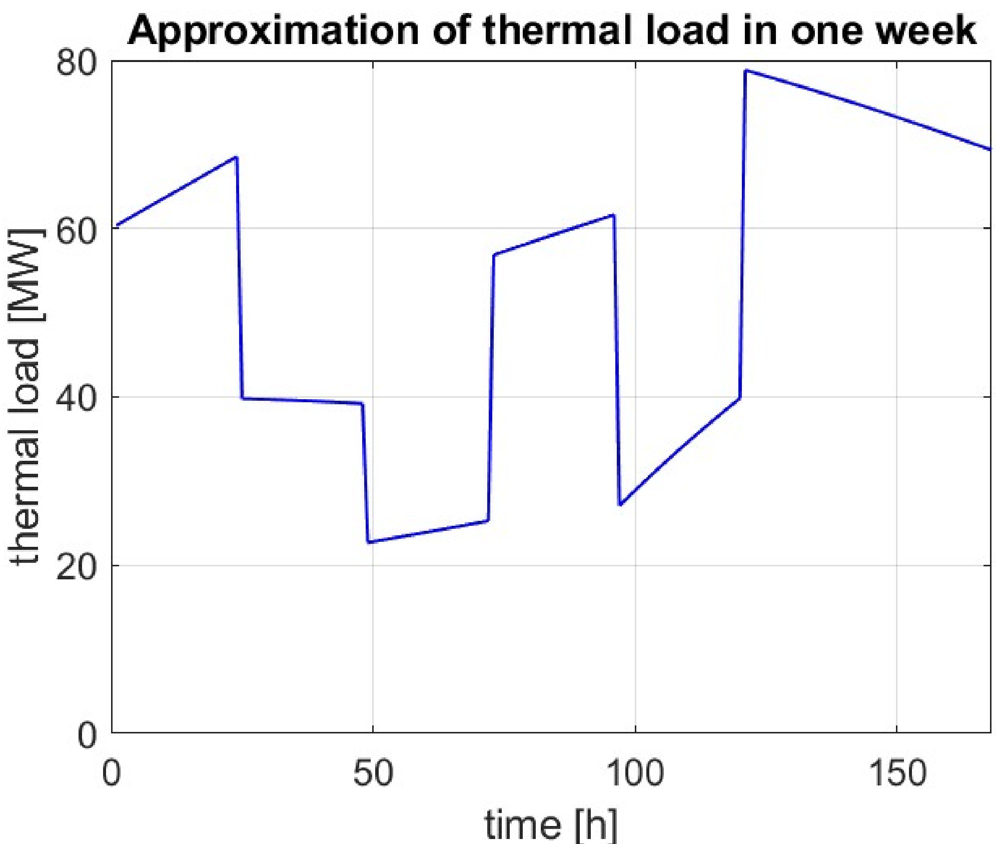

Figure 3: Thermal load at the furnace along one week

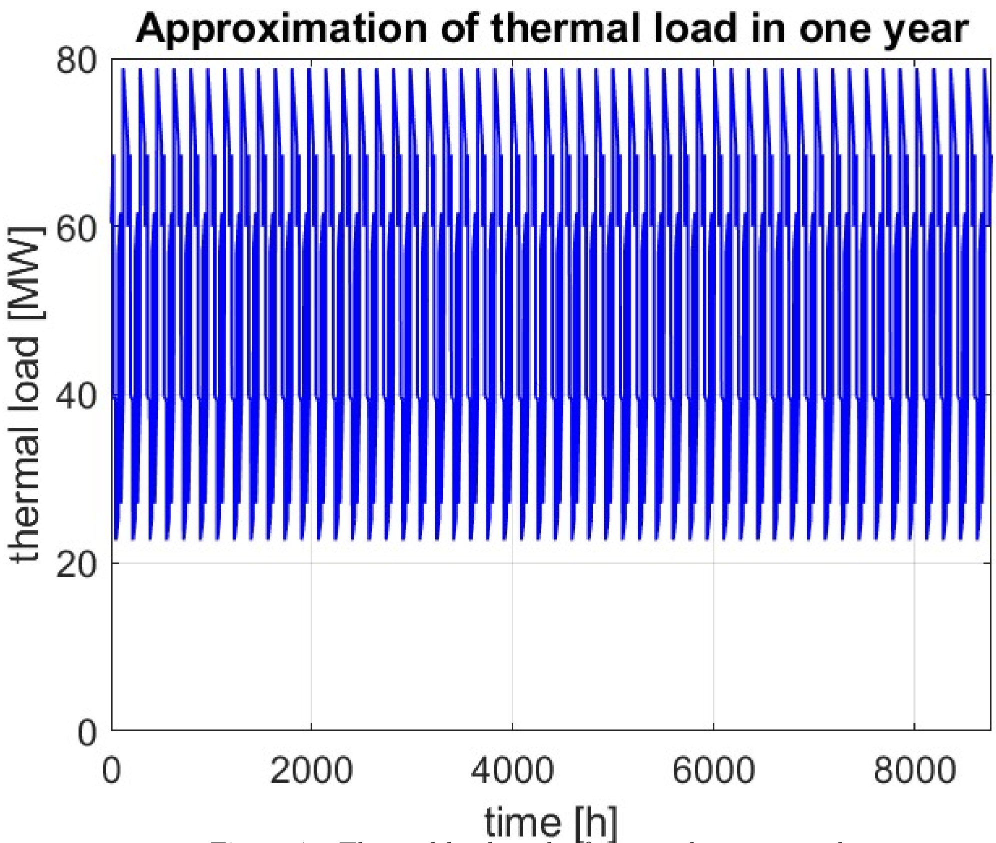

Figure 4: Thermal load at the furnace along one week

The objective function will consider moreover the CAPEX and OPEX costs related to the storage tank and the compressor. In order to perform sizing, also in this case the installed capacity, electrolyser rated power and burner rated power are considered as variables. The bottle tank capacity is fixed.

The objective function is set as follow:

$$C_{npcCAPEX} = P_{RATEDele} * c_{CAPEXele} + P_{RATEDele} * c_{INSTALLele} + \tag{20}$$

$$+ P_{RATEDele} * c_{REPLACEele} + P_{RATEDbur} * c_{CAPEXbur} + P_{RATEDbur} * c_{CAPEXbur} +$$

$$+ P_{RATEDht} * c_{CAPEXht} + m_{cp} * 3600 * c_{CAPEXcp} + m_{bo} * 3600 * c_{CAPEXbo}$$

$$C_{npcOPEX} = P_{RATEDele} * c_{OPEXele} + P_{RATEDbur} * c_{OPEXbur} \tag{21}$$

$$+ P_{RATEDht} * c_{OPEXht} + m_{cp} * 3600 * c_{OPEXcp} + m_{bo} * 3600 * c_{OPEXbo}$$

$$C_{electricityGRID} = \Sigma_{(t)}(P_{grid} * c_{electricitygrid}) \tag{22}$$

$$C_{electricityPV} = G_{PV} * c_{CAPEXpv} + G_{PV} * c_{OPEXpv} * lifetime \tag{23}$$

$$C_{npcTOT} = C_{npcCAPEX} + C_{npcOPEX} * lifetime + C_{electricityGRID} * lifetime + C_{electricityPV} \tag{24}$$

2.3.1 Results with realistic values

In order to make this model more realistic, I considered actual values for efficiencies, CAPEX, OPEX, costs and the other specificies. The main values of properties and general data of the plant are reported in the Table 2.

Specificity	Values	
Plant Life Time	20	[years]
Hydrogen Lower Heating value	33.33	[kWh/kg]
Hydrogen Density	0.0899	[kg/m^3]
Water Density	1000	[kg/m^3]
Hydrogen Flow Rate	420	[Nm^3/h]

Table 2: Properties and general data of the plant

The power supply is provided by PV generation and from a grid withdrawal. The Table 3 resumes the costs related to the power supply. The cost of electricity is referred to the Spain in year 2022 [3].

Specificity	Values	
electricity cost	0.2477	[€/$kWh * h$]
CAPEX$_{PV}$	1600	[€/kWe/year]
OPEX$_{PV}$	19	[USD/kW/year]

Table 3: Cost related to the power supply

The PV supply is considered by taking into account the data from Barcelona

The electrolyser data are considered by the datasheet of Hydrogen Cube System [7]. The data related to the hydrogen compressor,tank and burner are considered by the [5]. The data related to the hydrogen bottle tank are considered from the datasheets [4]. The Table 4 resumes all the data considered. The PV supply is considered by taking into account the data from Barcelona [1].

Specificity	Values	
Electrolyser		
Efficiency	75	[%]
Operating range	10-100	[%]
CAPEX	1188	[€/kW/year]
OPEX	15.84	[€/kW/year]
INSTALLATION costs	10	[%CAPEX]
stack REPLACEMENT costs	35	[%CAPEX]
Compressor		
Compression work	4	[MJ/kgH2]
CAPEX	1600	[€/kW/year]
OPEX	20.65	[€/kW/year]
Storage Tank		
Initial Level of Hydrogen	75	[%]
Operating range	10-90	[%]
CAPEX	470	[€/kgH_2/year]
OPEX	2	[%CAPEX]
Storage Bottle Tank		
Total volume	850	[liter]
CAPEX	470	[€/kgH_2/year]
OPEX	2	[%CAPEX]
Burner		
Efficiency	98	[%]
Operating range	0-100	[%]
CAPEX	63.32	[€/kW_{th}/year]
OPEX	5	[%CAPEX]

Table 4: Specificities of the components

The results obtained are reported in Figure 5, in Figure **??**, in Figure **??** and in Figure **??**.

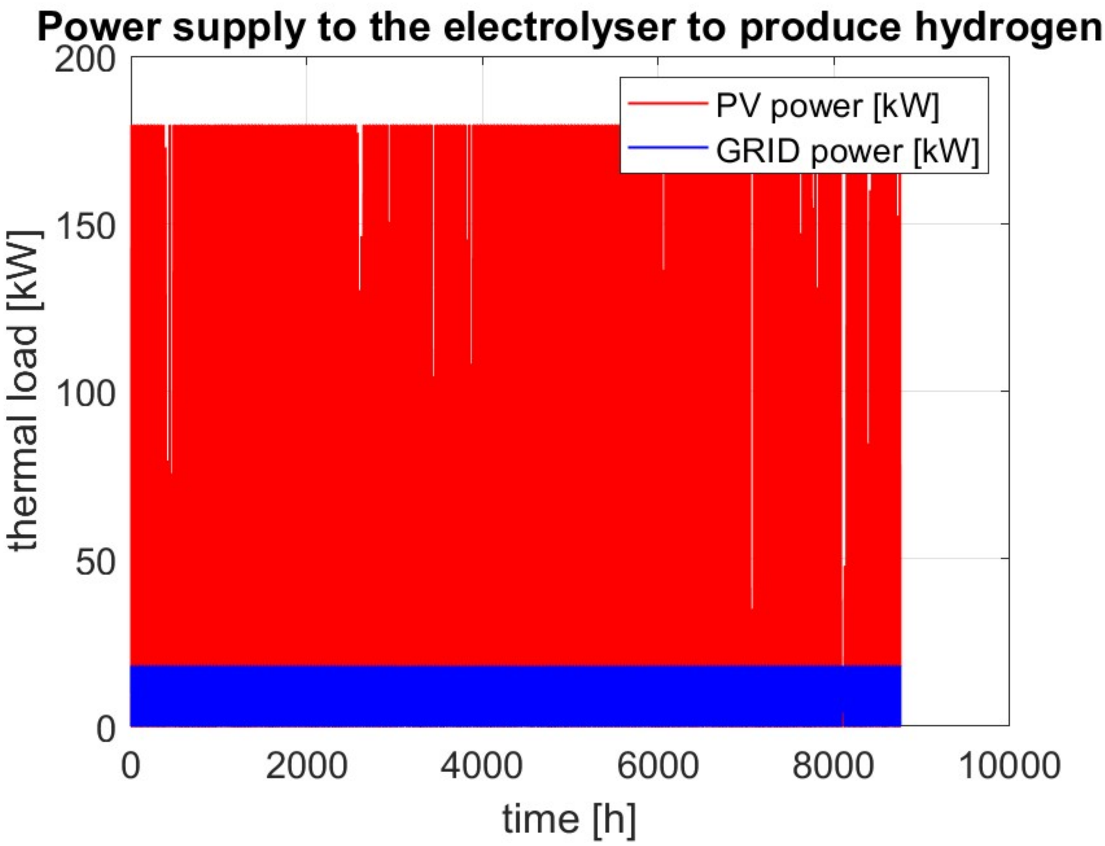

Figure 5: Comparison between the PV generation and the grid withdrawal

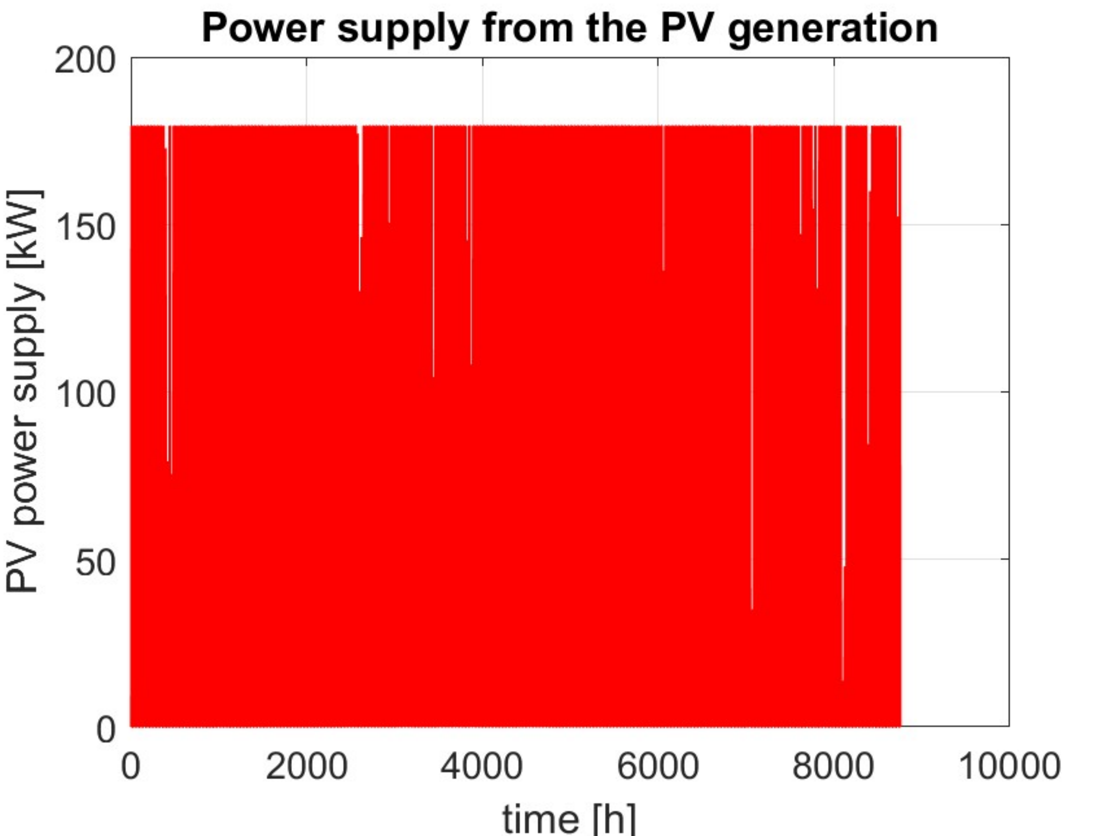

Figure 6: PV power supply along the year

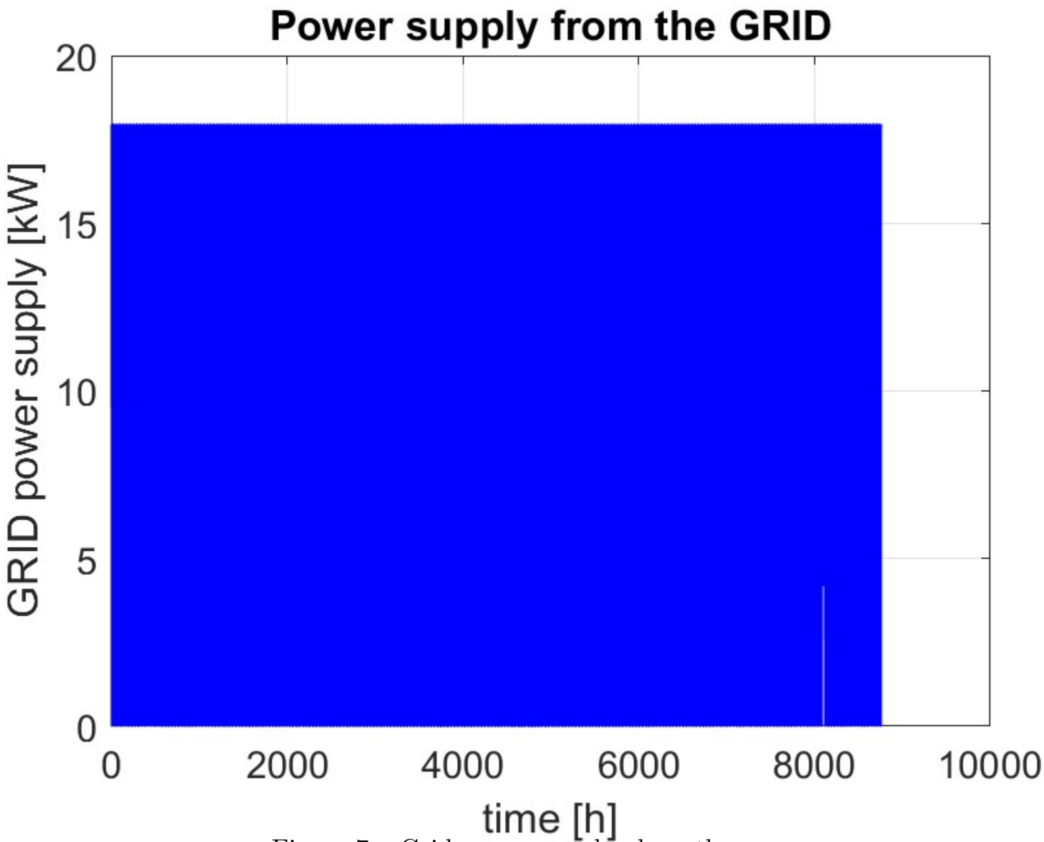

Figure 7: Grid power supply along the year

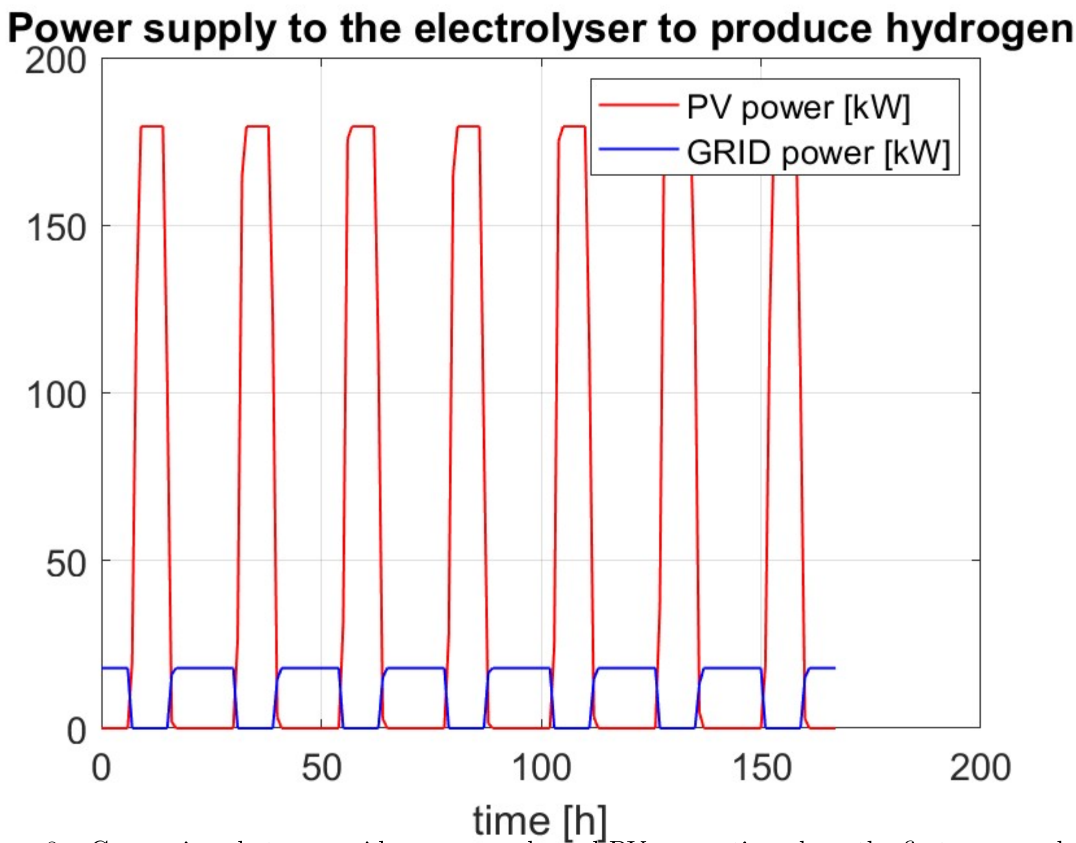

Figure 8: Comparison between grid power supply and PV generation along the first year week

References

[1] datos.gob.es. Hourly electricity demand in Catalonia per MWh, 2021.

[2] George D. Greenwade. The Comprehensive Tex Archive Network (CTAN). *TUGBoat*, 14(3):342–351, 1993.

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[5] Paolo Marocco, Marta Gandiglio, Davide Audisio, and Massimo Santarelli. Assessment of the role of hydrogen to produce high-temperature heat in the steel industry. *Journal of Cleaner Production*, 388:135969, 2023.

[6] Cecilia Springer and Ali Hasanbeigi. Emerging energy efficiency and carbon dioxide emissions-reduction technologies for the glass industry. 2017.

[7] H-TEC SYSTEM. Pem electrolyzers for a sustainable energy supply system – h-tec systems hydrogen cube system. 2023.