Hydrogen Microgrid: Notes and Physical Model

Lorenzo Bruno

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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: [1].

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

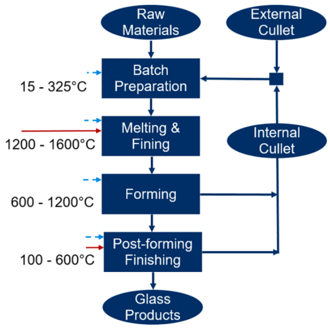

Figure 1: Explanation of the overall process temperatures for each step of the glass production process

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

3 Physical model

3.1 Model 1

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. We don't have any kind of storage: we imangine that the hydrogen produced is immediately burned

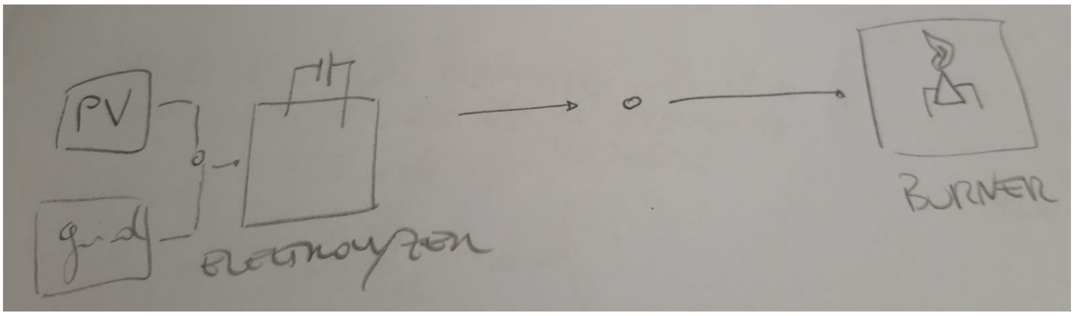

Figure 2: Model 1 considering electrolyser and burner

The power balance at Node 1:

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

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 at 1kWh and $F(t)$ is the PV power forecast.

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 of the system is:

$$P_{OUTele}(t) = P_{INbur}(t) \tag{6}$$

The conditions at the burner:

$$P_{OUTbur}(t) = \eta_{bur} \cdot P_{INbur}(t) \tag{7}$$

where η_{bur} is considered at 100%.

$$P_{INbur} \leq \lambda_{MAXbur} \cdot P_{RATEDbur} \tag{8}$$

$$P_{INbur} \geq \lambda_{MINbur} \cdot P_{RATEDbur} \tag{9}$$

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

The conditions at the load:

$$P_{OUTbur}(t) = P_{load}(t) \tag{10}$$

The objective function is set as follow:

$$C_{npcCAPEX} = P_{RATEDele} * c_{CAPEXele} + P_{RATEDbur} * c_{CAPEXbur} \tag{11}$$

$$C_{npcOPEX} = P_{RATEDele} * c_{OPEXele} + P_{RATEDbur} * c_{OPEXbur} \tag{12}$$

$$C_{electricityGRID} = \Sigma_{(t)}(P_{grid} * c_{electricitygrid}) \tag{13}$$

$$C_{electricityPV} = G_{PV} * c_{CAPEXpv} + G_{PV} * c_{OPEXpv} * lifetime \tag{14}$$

$$C_{npcTOT} = C_{npcCAPEX} + C_{npcOPEX} * lifetime + C_{electricityGRID} * lifetime + C_{electricityPV} \tag{15}$$

This is the operational optimization. In order to perform the sizing optimization, the installed capacity, electrolyser rated power and burner rated power are considered as variables.

3.2 Model 2

The Figure 3 shows the plant of this model. In this section we consider that the electrolyser is fed by the grid and PV generation. The tank is inserted between the Node 2 and Node 3.

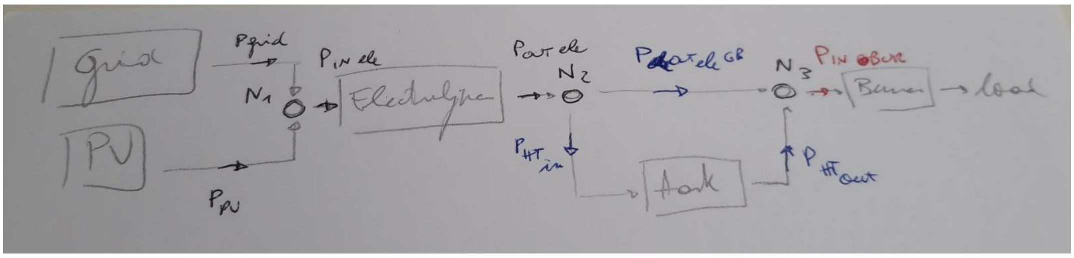

Figure 3: Model 2 considering electrolyser, tank and burner

The power balance at Node 1:

$$P_{grid}(t) + P_{PV}(t) = P_{INele}(t) \tag{16}$$

The definition of the PV generation:

$$P_{PV}(t) \leq G_{PV} \cdot F(t) \tag{17}$$

where G_{PV} is the rated PV installed capacity at 1kWh and $F(t)$ is the PV power forecast.
The conditions at the electrolyser:

$$P_{OUTele}(t) = \eta_{ele} \cdot P_{INele}(t) \tag{18}$$

where η_{ele} is considered around 80%.

$$P_{INele} \leq \lambda_{MAXele} \cdot P_{RATEDele} \tag{19}$$

$$P_{INele} \geq \lambda_{MINele} \cdot P_{RATEDele} \tag{20}$$

where $P_{RATEDele}$ is the rated power at 1MW.
The power balance at Node 2:

$$P_{OUTele}(t) = P_{INHT}(t) + P_{OUTeleGB}(t) \tag{21}$$

The conditions at the Hydrogen Tank:

$$E_{HT}(t) = E_{HT}(t-1) + P_{INHT}(t) \cdot \Delta t - P_{OUTHT}(t) \cdot \Delta t \tag{22}$$

$$E_{HT}(t_{in}) = LOH_{in} \cdot E_{RATED} \tag{23}$$

$$E_{HT} \leq LOH_{MAX} \cdot E_{RATED} \tag{24}$$

$$E_{HT} \geq LOH_{MIN} \cdot E_{RATED} \tag{25}$$

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 power balance at Node 3:

$$P_{OUTeleGB}(t) + P_{OUTHT}(t) = P_{INbur}(t) \tag{26}$$

The conditions at the burner:

$$P_{OUTbur}(t) = \eta_{bur} \cdot P_{INbur}(t) \tag{27}$$

where η_{bur} is considered at 100%.

$$P_{INbur} \leq \lambda_{MAXbur} \cdot P_{RATEDbur} \tag{28}$$

$$P_{INbur} \geq \lambda_{MINbur} \cdot P_{RATEDbur} \tag{29}$$

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

The conditions at the load:

$$P_{OUTbur}(t) = P_{load}(t) \tag{30}$$

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

The objective function is set as follow:

$$C_{npcCAPEX} = P_{RATEDele} * c_{CAPEXele} + P_{RATEDbur} * c_{CAPEXbur} + P_{RATEDht} * c_{CAPEXht} \tag{31}$$

$$C_{npcOPEX} = P_{RATEDele} * c_{OPEXele} + P_{RATEDbur} * c_{OPEXbur} + P_{RATEDht} * c_{OPEXht} \tag{32}$$

$$C_{electricityGRID} = \Sigma_{(t)}(P_{grid} * c_{electricitygrid}) \tag{33}$$

$$C_{electricityPV} = G_{PV} * c_{CAPEXpv} + G_{PV} * c_{OPEXpv} * lifetime \tag{34}$$

$$C_{npcTOT} = C_{npcCAPEX} + C_{npcOPEX} * lifetime + C_{electricityGRID} * lifetime + C_{electricityPV} \tag{35}$$

3.3 Model 3

The Figure 4 shows the plant of this model. In this section we consider that the electrolyser is fed by the grid and PV generation. The tank is inserted between the Node 2 and Node 3. The compressor is added: it is fed by the mixture of grid and PV supply from node 1.

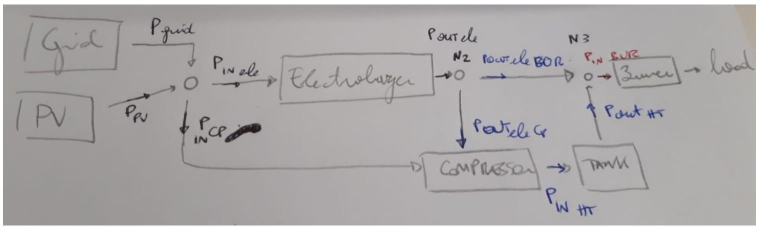

Figure 4: Model 3 considering electrolyser, compressor, tank and burner

The power balance at Node 1:

$$P_{grid}(t) + P_{PV}(t) = P_{INele}(t) + P_{INCP}(t) \tag{36}$$

The definition of the PV generation:

$$P_{PV}(t) \leq G_{PV} \cdot F(t) \tag{37}$$

where G_{PV} is the rated PV installed capacity at 1kWh and $F(t)$ is the PV power forecast.
The conditions at the electrolyser:

$$P_{OUTele}(t) = \eta_{ele} \cdot P_{INele}(t) \tag{38}$$

where η_{ele} is considered around 80%.

$$P_{INele} \leq \lambda_{MAXele} \cdot P_{RATEDele} \tag{39}$$

$$P_{INele} \geq \lambda_{MINele} \cdot P_{RATEDele} \tag{40}$$

where $P_{RATEDele}$ is the rated power at 1MW.
The power balance at Node 2:

$$P_{OUTele}(t) = P_{INHT}(t) + P_{OUTeleGB}(t) \tag{41}$$

The conditions at the Hydrogen Tank:

$$P_{INHT}(t) = \frac{P_{OUTele}(t) \cdot l_{CP}}{LHV_{H2}} \tag{42}$$

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

$$P_{OUTeleCP}(t) = P_{INHT}(t) \tag{43}$$

The conditions at the Hydrogen Tank:

$$E_{HT}(t) = E_{HT}(t-1) + P_{INHT}(t) \cdot \Delta t - P_{OUTHT}(t) \cdot \Delta t \tag{44}$$

$$E_{HT}(t_{in}) = LOH_{in} \cdot E_{RATED} \tag{45}$$

$$E_{HT} \leq LOH_{MAX} \cdot E_{RATED} \tag{46}$$

$$E_{HT} \geq LOH_{MIN} \cdot E_{RATED} \tag{47}$$

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 power balance at Node 3:

$$P_{OUTeleGB}(t) + P_{OUTHT}(t) = P_{INbur}(t) \tag{48}$$

The conditions at the burner:

$$P_{OUTbur}(t) = \eta_{bur} \cdot P_{INbur}(t) \tag{49}$$

where η_{bur} is considered at 100%.

$$P_{INbur} \leq \lambda_{MAXbur} \cdot P_{RATEDbur} \tag{50}$$

$$P_{INbur} \geq \lambda_{MINbur} \cdot P_{RATEDbur} \tag{51}$$

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

The conditions at the load:

$$P_{OUTbur}(t) = P_{load}(t) \tag{52}$$

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 objective function is set as follow:

$$C_{npcCAPEX} = P_{RATEDele}*c_{CAPEXele}+P_{RATEDbur}*c_{CAPEXbur}+P_{RATEDht}*c_{CAPEXht}+P_{RATEDcp}*c_{CAPEXcp} \tag{53}$$

$$C_{npcOPEX} = P_{RATEDele}*c_{OPEXele}+P_{RATEDbur}*c_{OPEXbur}+P_{RATEDht}*c_{OPEXht}+P_{RATEDcp}*c_{OPEXcp} \tag{54}$$

$$C_{electricityGRID} = \Sigma_{(t)}(P_{grid} * c_{electricitygrid}) \tag{55}$$

$$C_{electricityPV} = G_{PV} * c_{CAPEXpv} + G_{PV} * c_{OPEXpv} * lifetime \tag{56}$$

$$C_{npcTOT} = C_{npcCAPEX} + C_{npcOPEX} * lifetime + C_{electricityGRID} * lifetime + C_{electricityPV} \tag{57}$$

3.3.1 Results

By adding the compressor I have also written the part of the script to extract data. I am now able to print the results of the PV generation and the grid contribution. I plot them and I show them below.

The Figure 5 shows the thermal load requested at the furnace. We consider a constant load of about 251 kW per hour, considering an average supply of a steel furnace of 42.2 MW per week. The Figure 6 shows the PV power supply from the data evaluated for the location of Barcelona. It is evident that the highest amount of power that is requested is around 1200 kW: this value takes into account the different losses due to conversion of electric power into hydrogen and the energy for the compression storage. The Figure 7 shows the grid power supply, compensating the PV power request. As we can see, the summer time is the period where the grid withdrawal is the lowest.

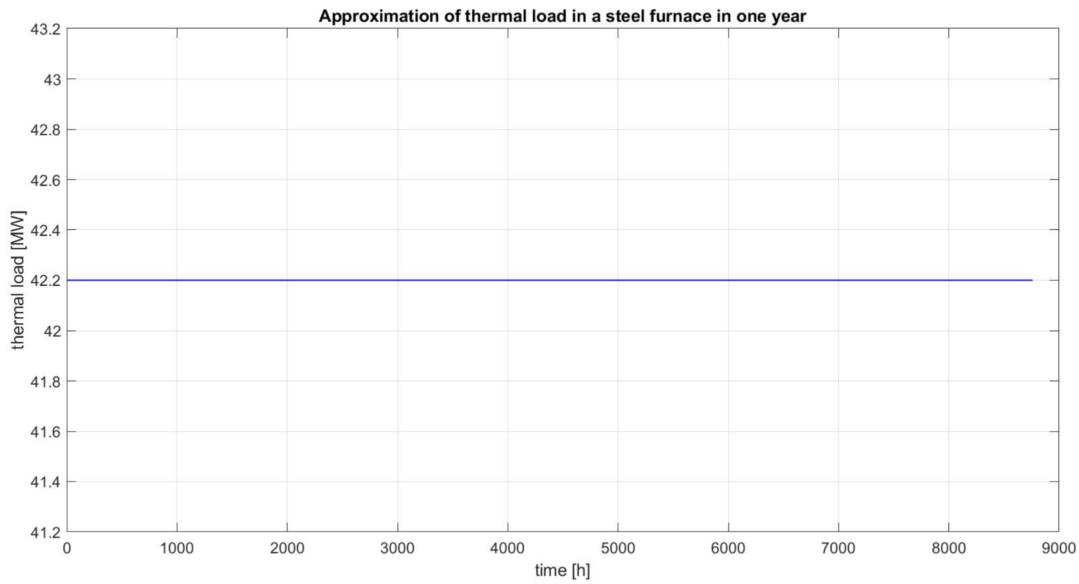

Figure 5: Constant thermal load of 42.2 MW average for each week

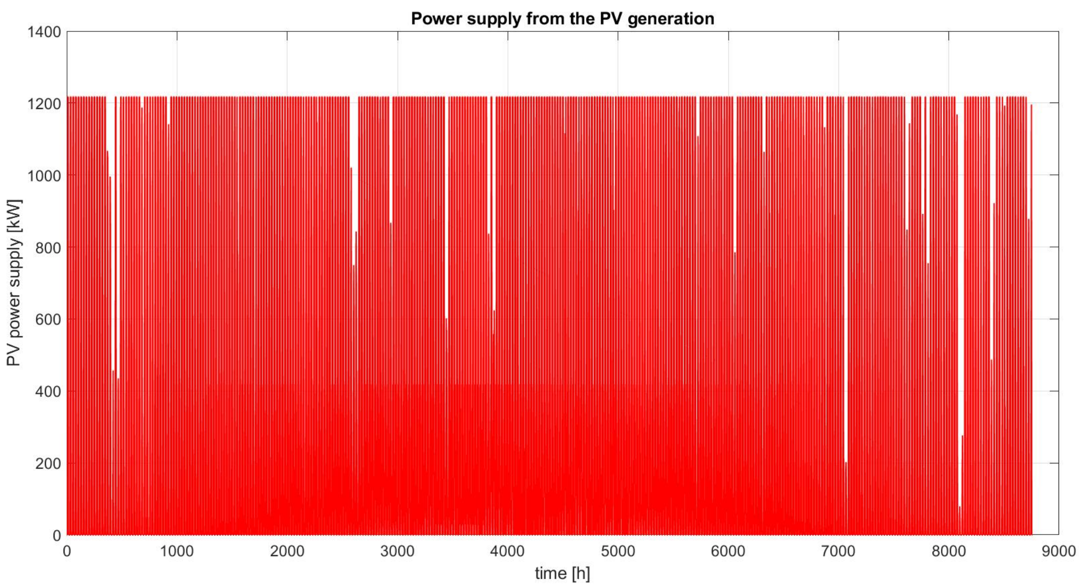

Figure 6: PV power supply along the year

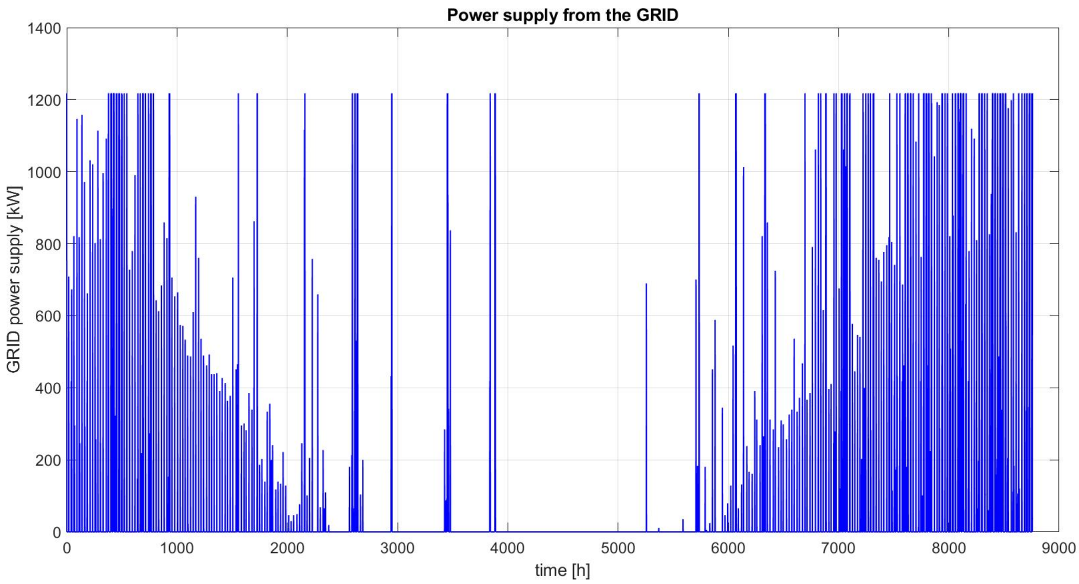

Figure 7: Grid power supply along the year

3.4 Model 4

The Figure 8 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.

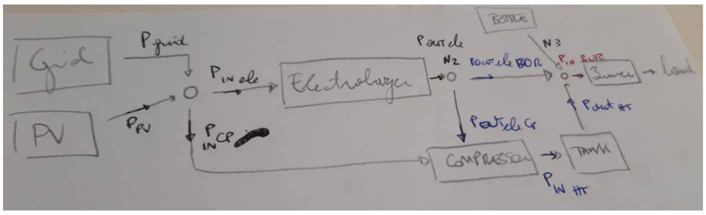

Figure 8: Model 4 considering electrolyser, compressor, tank, bottle tank and burner

The power balance at Node 1:

$$P_{grid}(t) + P_{PV}(t) = P_{INele}(t) + P_{INCP}(t) \tag{58}$$

The definition of the PV generation:

$$P_{PV}(t) \leq G_{PV} \cdot F(t) \tag{59}$$

where G_{PV} is the rated PV installed capacity at 1kWh and $F(t)$ is the PV power forecast.
The conditions at the electrolyser:

$$P_{OUTele}(t) = \eta_{ele} \cdot P_{INele}(t) \tag{60}$$

where η_{ele} is considered around 80%.

$$P_{INele} \leq \lambda_{MAXele} \cdot P_{RATEDele} \tag{61}$$

$$P_{INele} \geq \lambda_{MINele} \cdot P_{RATEDele} \tag{62}$$

where $P_{RATEDele}$ is the rated power at 1MW.
The power balance at Node 2:

$$P_{OUTele}(t) = P_{INHT}(t) + P_{OUTeleGB}(t) \tag{63}$$

The conditions at the Hydrogen Tank:

$$P_{INHT}(t) = \frac{P_{OUTele}(t) \cdot l_{CP}}{LHV_{H2}} \tag{64}$$

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

$$P_{OUTeleCP}(t) = P_{INHT}(t) \tag{65}$$

The conditions at the Hydrogen Tank:

$$E_{HT}(t) = E_{HT}(t-1) + P_{INHT}(t) \cdot \Delta t - P_{OUTHT}(t) \cdot \Delta t \tag{66}$$

$$E_{HT}(t_{in}) = LOH_{in} \cdot E_{RATED} \tag{67}$$

$$E_{HT} \leq LOH_{MAX} \cdot E_{RATED} \tag{68}$$

$$E_{HT} \geq LOH_{MIN} \cdot E_{RATED} \tag{69}$$

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:

$$E_{bo}(t) = E_{bo}(t-1) - P_{OUTbo}(t) \cdot \Delta t \tag{70}$$

$$E_{bo}(t_{in}) = E_{RATEDbo} \tag{71}$$

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

The power balance at Node 3:

$$P_{OUTeleGB}(t) + P_{OUTHT}(t) + P_{OUTbo}(t) = P_{INbur}(t) \tag{72}$$

The conditions at the burner:

$$P_{OUTbur}(t) = \eta_{bur} \cdot P_{INbur}(t) \tag{73}$$

where η_{bur} is considered at 100%.

$$P_{INbur} \leq \lambda_{MAXbur} \cdot P_{RATEDbur} \tag{74}$$

$$P_{INbur} \geq \lambda_{MINbur} \cdot P_{RATEDbur} \tag{75}$$

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

The conditions at the load:

$$P_{OUTbur}(t) = P_{load}(t) \tag{76}$$

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:

$$C_{npcCAPEX} = P_{RATEDele} * c_{CAPEXele} + P_{RATEDbur} * c_{CAPEXbur} \tag{77}$$

$$+P_{RATEDht} * c_{CAPEXht} + P_{RATEDcp} * c_{CAPEXcp} + P_{RATEDbo} * c_{CAPEXbo}$$

$$C_{npcOPEX} = P_{RATEDele} * c_{OPEXele} + P_{RATEDbur} * c_{OPEXbur} \tag{78}$$

$$+P_{RATEDht} * c_{OPEXht} + P_{RATEDcp} * c_{OPEXcp} + P_{RATEDbo} * c_{OPEXbo}$$

$$C_{electricityGRID} = \Sigma_{(t)}(P_{grid} * c_{electricitygrid}) \tag{79}$$

$$C_{electricityPV} = G_{PV} * c_{CAPEXpv} + G_{PV} * c_{OPEXpv} * lifetime \tag{80}$$

$$C_{npcTOT} = C_{npcCAPEX} + C_{npcOPEX} * lifetime + C_{electricityGRID} * lifetime + C_{electricityPV} \tag{81}$$

3.4.1 Results

By adding the bottle tank, we expect a reduction of the power supply from the grid. the following results show this evolution.

The Figure 9 shows the PV power supply from the data evaluated for the location of Barcelona. The Figure 10 shows the grid power supply, compensating the PV power request. As we can see by the comparison with Figure 7, the amount of power requested by the grid is lower in this case. The Figure 11 shows the weekly behaviour of the evolution of power supply of PV generation and from the grid

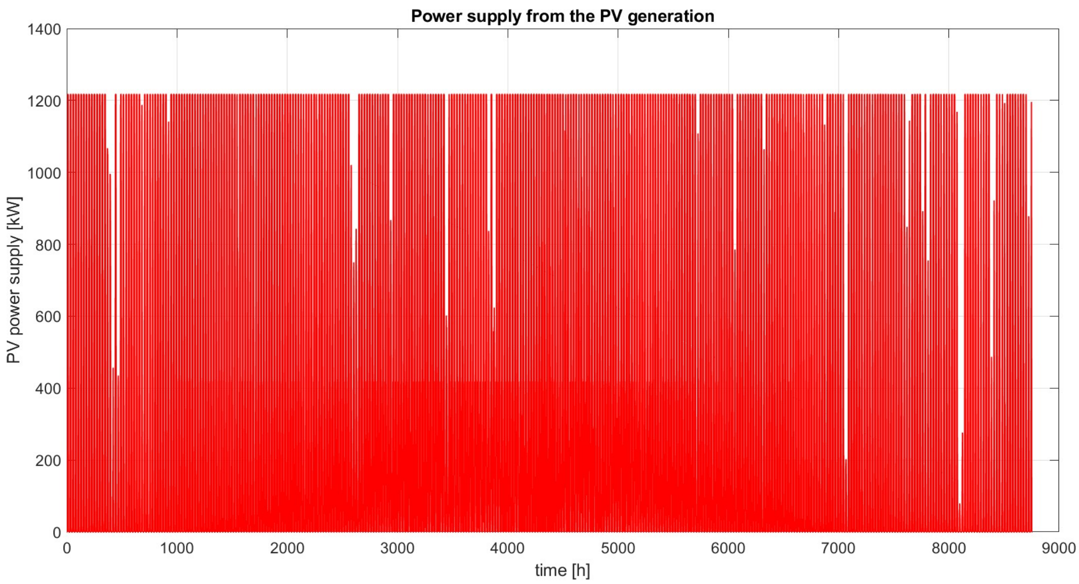

Figure 9: PV power supply along the year

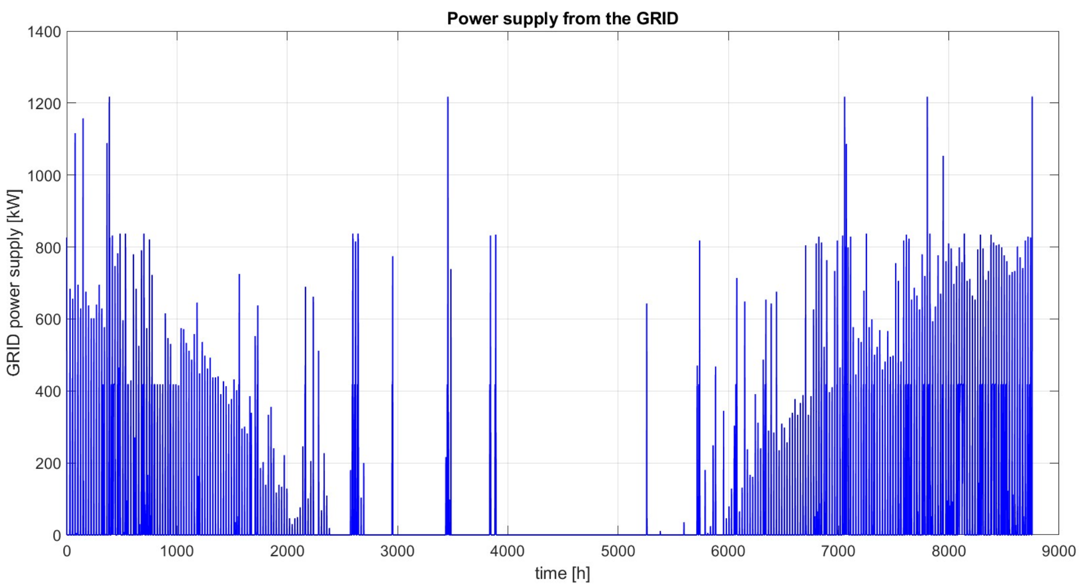

Figure 10: Grid power supply along the year

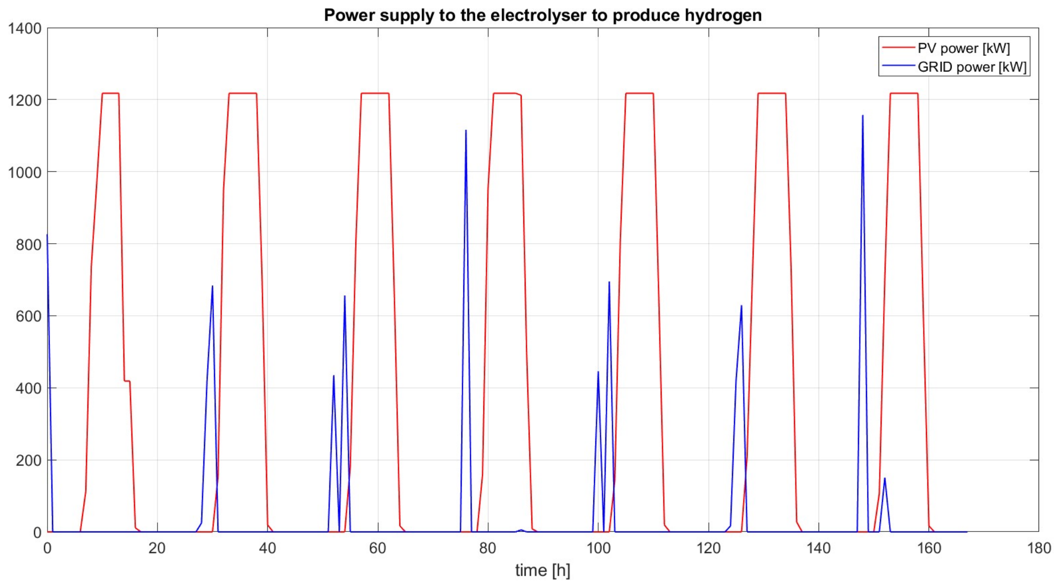

Figure 11: Grid and PV power supply along the first week of the year

References

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