Hydrogen Microgrid: Notes and Physical Model

Lorenzo Bruno

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1 Introduction

In the context of the decarbonation of the high-temperature industry, the H2GLASS project focuses on the production of hydrogen in order to substitute the natural gas in the combustion at the furnace: in this project hydrogen will be the fuel for the furnace combustion into a glass industry . 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 connected to a grid, where the hydrogen can be directly burnt at the burner or can be stored by means of a storage system. The power load oscillates between 20 and 80 MW. A storage bottle tank is connected to the grid to supply the storage system.

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

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

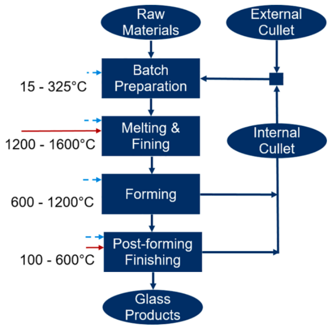

Figure 1: Explanation of the overall process temperatures for each step of the glass production process

time of the batch mixture. In Germany the residence time can vary between 5 and 24 h, with an average value of 12 h.

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.

The main hypothesys taken into account concern:

1. Only one burner considered
2. The furnace cost is considered in operating on the cost as function of CAPEX
3. I don't consider discount rate
4. The number of stack substitution is two along the 20 years lifetime of the plant

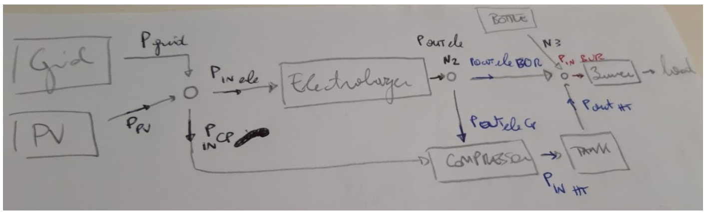

Figure 2: Model 4 considering electrolyser, compressor, tank, bottle tank and burner

The definition of the PV generation:

$$P_{PV}(t) \leq G_{PV} \cdot F(t) \tag{1}$$

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 power balance at Node 1:

$$P_{grid}(t) + P_{PV}(t) = P_{INele}(t) + P_{INCP}(t) \tag{2}$$

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

The conditions at the electrolyser:

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

where η_{ele} is considered around 65%.

The further conditions imposed on the electrolyser are important to set the status of activation and deactivation as a function of the thermal load. For this purpose it is introduced the variable $\delta_{ele(t)}$ equal to 0 or 1, defining the on/off status. It is depending on time and it is zero if the load is lower than a certain value, so that the electrolyser is shut down and there is no production of hydrogen. The correlation between the power rated of the electrolyser and the $\delta_{ele}(t)$ is stated in the equation:

$$P_{OPTele} = P_{OUTele}(t) - P_{INele}(t) \tag{4}$$

$$z_{ONele} = \delta_{ele}(t) \cdot P_{OPTele}(t) \tag{5}$$

where the P_{OPTele} is the optimized power defined as follow

The problem showed in this way presents a non linearity: both the $\delta_{ele(t)}$ and the $P_{OPTele}(t)$ are decision variables. In order to linearize the problem, the variable z_{ONele} is introduced: the following set of inequalities defines the variable.

$$-M \cdot \delta_{ele}(t) \leq z_{ONele}(t) \leq M \cdot \delta_{ele}(t) \tag{6}$$

$$-M \cdot (1 - \delta_{ele}(t)) \leq z_{ONele}(t) - P_{OPTele} \leq M \cdot (1 - \delta_{ele}(t)) \tag{7}$$

where M is equal to 10'000'000 kW, in order to provide the widest range possible to choose the variable of the system.

Another kind of condition imposed on the electrolyser is related to the ramp up assumption:

$$|P_{OUTele}(t) - P_{OUTele}(t-1)| \leq P_{PVrampup} \tag{8}$$

where P_{PV_rampup} is the ramp up value expressed in [MW/min]. This condition is related to the variation of the derivative of the PV power ratio for each timestep.

The power balance at Node 2:

$$P_{OUTele}(t) = P_{OUTeleCP}(t) + P_{OUTeleBUR}(t) \tag{9}$$

The Node 2 represents the flow rate split where a part of the hydrogen produced goes directly to the burner, while the other part feeds the compressor for the storage tank.

The conditions at the compressor:

$$P_{INCP}(t) = \frac{P_{OUTeleCP}(t) \cdot l_{CP}}{LHV_{H2}} \tag{10}$$

where l_{CP} is the compression specific work and LHV_{H2} is the Lower Heating Value of hydrogen. The energy balance at the compressor consider the ower from the grid, the power from the electrolyser and the power injected in the storage.

$$P_{INCP}(t) + P_{OUTeleCP}(t) = P_{INHT}(t) \tag{11}$$

The conditions at the Hydrogen Tank:

$$E_{HT}(t) = E_{HT}(t-1) + P_{INHT}(t) \cdot \Delta t - P_{OUTHT}(t) \cdot \Delta t \tag{12}$$

$$E_{HT}(t_{in}) = LOH_{in} \cdot E_{RATED} \tag{13}$$

$$LOH_{MIN} \cdot E_{RATED} \leq E_{HT}(t) \leq LOH_{MAX} \cdot E_{RATED} \tag{14}$$

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. We consider moreover that the last value of storage tank corrisponds equal with the first value of the following year

The conditions at the Hydrogen Bottle Tank:

$$E_{bo}(t) = E_{bo}(t-1) - P_{OUTbo}(t) \cdot \Delta t \tag{15}$$

$$E_{bo}(t_{in}) = E_{RATEDbo} \tag{16}$$

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

The power balance at Node 3:

$$P_{OUTeleBUR}(t) + P_{OUTHT}(t) + P_{OUTbo}(t) = P_{INbur}(t) \tag{17}$$

The conditions at the burner:

$$P_{OUTbur}(t) = \eta_{bur} \cdot P_{INbur}(t) \tag{18}$$

where η_{bur} is considered at 95%.

$$\lambda_{MINbur} \cdot P_{RATEDbur} \leq P_{INbur} \leq \lambda_{MAXbur} \cdot P_{RATEDbur} \tag{19}$$

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

The conditions at the load:

$$P_{OUTbur}(t) = P_{load}(t) \tag{20}$$

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.

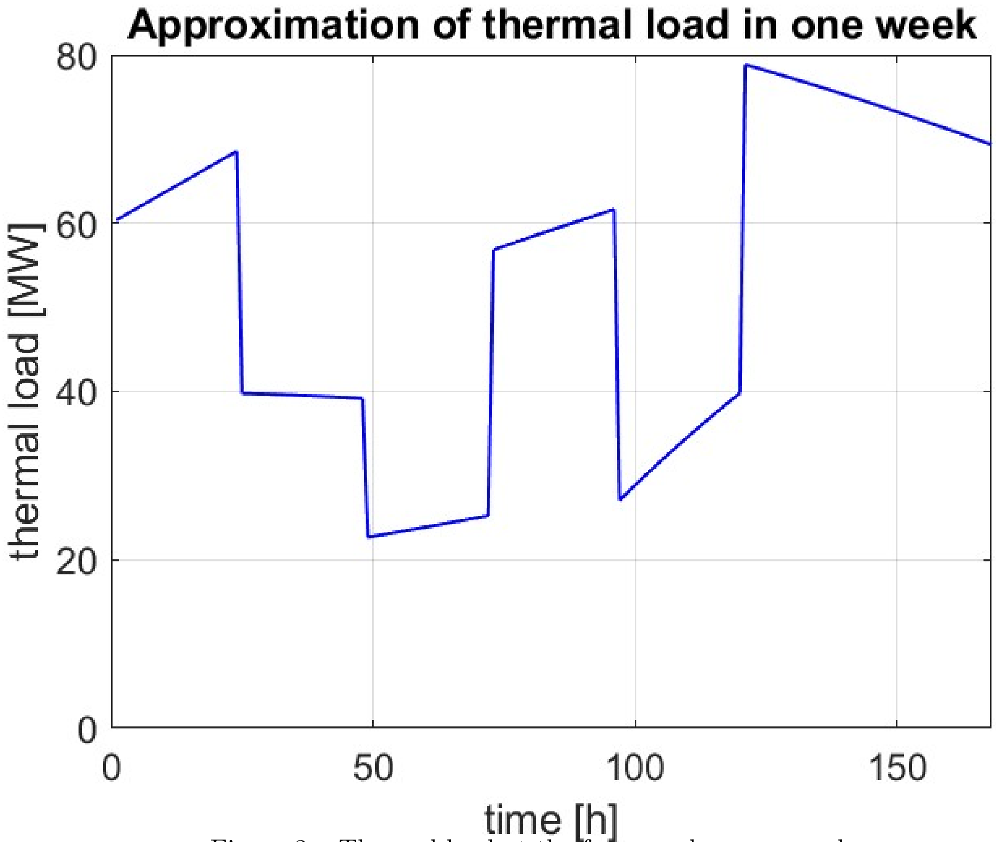

Figure 3: Thermal load at the furnace along one week

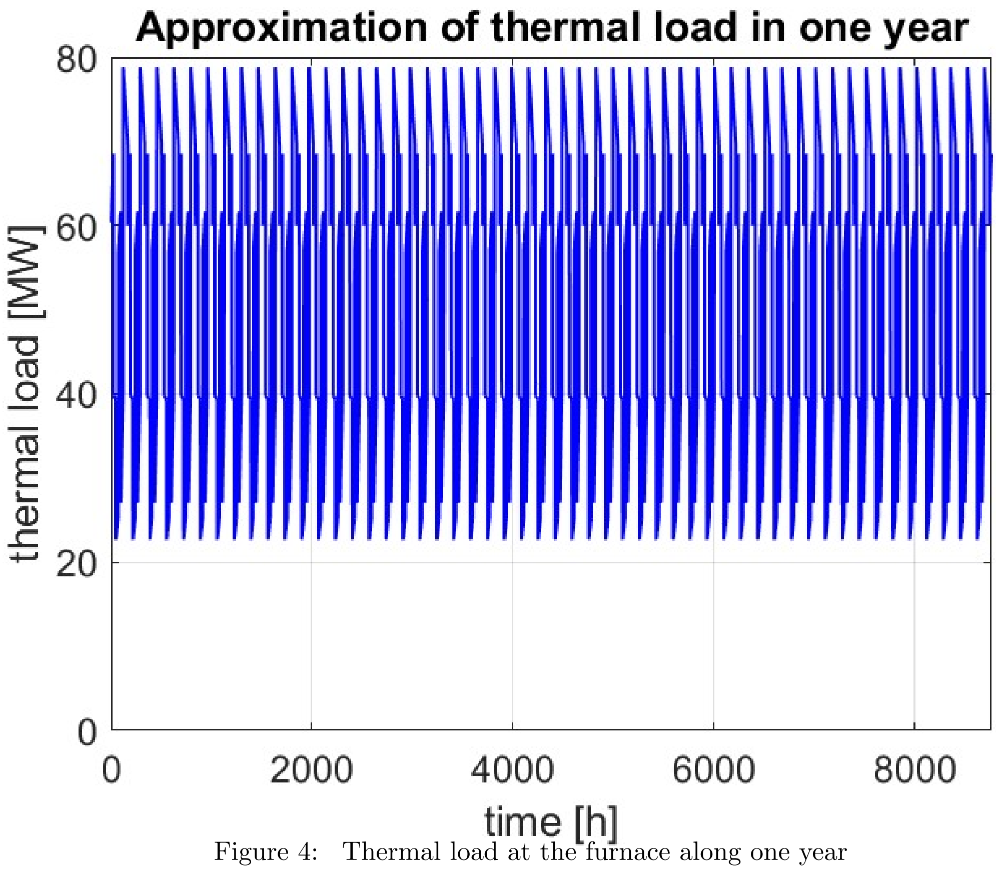

Figure 4: Thermal load at the furnace along one year

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:

$$C_{npcCAPEX} = P_{RATEDele} * c_{CAPEXele} + P_{RATEDele} * c_{INSTALLele} + \tag{21}$$
$$+ P_{RATEDele} * c_{REPLACEele} * n_{replace} + m_{RATEDbur} * c_{CAPEXbur} + P_{RATEDbur} * c_{CAPEXbur} +$$
$$+ P_{RATEDht} * c_{CAPEXht} + m_{cp} * 3600 * c_{CAPEXcp} + m_{bo} * 3600 * c_{CAPEXbo}$$

$$C_{npcOPEX} = P_{RATEDele} * c_{OPEXele} + P_{RATEDbur} * c_{OPEXbur} \tag{22}$$
$$+ m_{cp} * 3600 * c_{OPEXcp} + P_{RATEDht} * c_{OPEXht} + + m_{bo} * 3600 * c_{OPEXbo}$$

$$C_{electricityGRID} = \Sigma_{(t)}(P_{grid} * c_{electricitygrid}) \tag{23}$$

$$C_{electricityPV} = G_{PV} * c_{CAPEXpv} + G_{PV} * c_{OPEXpv} * lifetime \tag{24}$$

$$C_{npcTOT} = C_{npcCAPEX} + C_{npcOPEX} * lifetime + C_{electricityGRID} * lifetime + C_{electricityPV} \tag{25}$$

The economic indicators that we consider for the comparison between different scenarios are Levelized Cost of thermal Energy and Levelized Cost of Hydrogen; as the environmental indicator the total amount of carbon dioxide produced by the plant.

1. the Levelized Cost of thermal Energy is defined by the ratio of total Net Present Cost C_{NPCtot} over the annual demand of thermal energy E_t

$$LCOE_t = \frac{C_{NPCtot}}{\Sigma E_t * (1+d)^{-n}} \tag{26}$$

where the d is the discount rate and n is the year at which the summation is done

2. the Levelized Cost of Hydrogen is defined by the ratio of total Net Present Cost C_{NPCtot} over the annual production of hydrogen M_{hyd}

$$LCOH = \frac{C_{NPCtot}}{\Sigma M_{hyd} * (1+d)^{-n}} \tag{27}$$

3. the total amount of carbon dioxide is evaluated by multiplying the total amount of power withdrawl by the the grid by the power sector emission intensity ECI estimated in $[\frac{gCO2}{kWh}]$

$$M_{CO_2} = C_{NPCtot} * ECI \tag{28}$$

where the production of energy injected in the grid is supposed to be provided by natural gas.

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	500	[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$_{grid}$	0.2966	[€/$kWh*h$]
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	65	[%]
Operating range	10-100	[%]
Ramp up value	60	[MW/min]
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	235	[€/kgH_2/year]
OPEX	2	[%CAPEX]
Burner		
Efficiency	95	[%]
Operating range	0-100	[%]
CAPEX	63.32	[€/kW_{th}/year]
OPEX	5	[%CAPEX]

Table 4: Specificities of the components

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.

[3] Electricity in Spain. Electricity Prices in Spain, 1999.

[4] MAHYTEC. Product : Hydrogen tank 60bar – 850l, 2021.

[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.