Politecnico di Torino

M.Sc. in Energy and Nuclear Engineering –

Renewable Energy Systems

Master Thesis

Feasibility study for partial decarbonization of the closure production process in Indian factories

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Abstract

This work aims at proposing a combination of renewable technologies to partially decarbonize the process of four Indian factories that produce plastic closures in 2030.

The first part is dedicated to the study of the closure process and the related input energy vectors. The energy consumption and the emissions are normalized to the production for each factory to have a comparison and to detect which factories require a strong emission reduction.

Chosen the factories and basing to the location (India), photovoltaic panels and Proton-Exchange Membrane technologies are proposed, together with a suitable storage system, and their productivity is studied using formulas and parameters taken from literature. The optimal PV size proposed by a software (Homer Pro) is obtained from a simulation in which only PV is present, and it is used as input in an Excel algorithm to calculate the excess of energy and to dimension suitable technology capacities. Results show a good share of renewables in most of the selected factories and a strong emission reduction. Both parameters can be improved by varying the installed capacities.

The final part concerns the techno-economic analysis to understand the investment required for each factory and the related revenues if present. Results show that the chosen technology sizes do not bring a positive Net Present Value with the assumed economic values and therefore either a stronger price reduction for PEM technologies and PV or a higher increasing rate in electricity price is required to make the investment economically feasible.

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List of acronyms

Acronym	Meaning
AL	Aluminium
BOP	Balance Of Plant
CAPEX	Capital Expenditure
FC	Fuel Cell
PL	Plastic
GHG	Greenhouse gas
GWP	Global Warming Potential
HX	Heat Exchanger
IPP	Independent Power Produces
IOU	Investor-Owned Utility
LHV	Lower Heating Value
NPV	Net Present Value
O&M	Operation & Maintenance
OPEX	Operation Expenditure
PEMEC	Proton-Exchange Membrane Electrolyser
PEMFC	Proton-Exchange Membrane Fuel Cell
PV	Photovoltaic
SC	Specific Consumption
WACC	Weight Average Cost of Capital

Introduction

Industry is nowadays the largest energy consumer among end-use sectors [1], accounting for 45% of the global primary energy consumption [2], corresponding to 250 EJ in 2018. According to the bp Energy Outlook 2020, this value will grow with a different rate according to the incoming scenario, as shown in figure 1.

Three scenarios have been considered [2]:

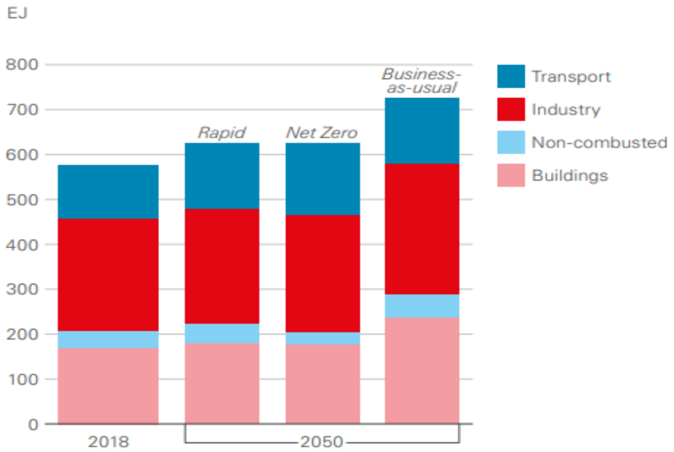

Figure 1 - Global Primary Energy Consumption by end - use sector [2]

- Rapid Transition Scenario: it assumes a series of actions aimed at increasing carbon prices and decreasing carbon emissions by 70% in 2050
- Net Zero Scenario: it considers the same actions of the Rapid Scenario with a higher sensibilisation and change in societal behaviour aimed at lowering the global carbon emission by 95%
- Business –as– usual Scenario: it assumes that no overwhelming policies are taken. The social and technological process continues to evolve slowly with a speed and a manner like the recent past

In the optimistic scenarios the growth in demand is almost flat, differently from the BAU that shows an increase of energy demand of 15%, as depicted in figure 2. Since industry accounts for a large share of the total consumed energy in the world, its limitation in growth is crucial in order to restrict the global carbon emissions (figure 3). Unfortunately, big efforts are required to follow the Rapid and Net Zero trend: circular economy must be expanded, industrial processes must be more efficient and "green" and carbon capture must be implemented [2].

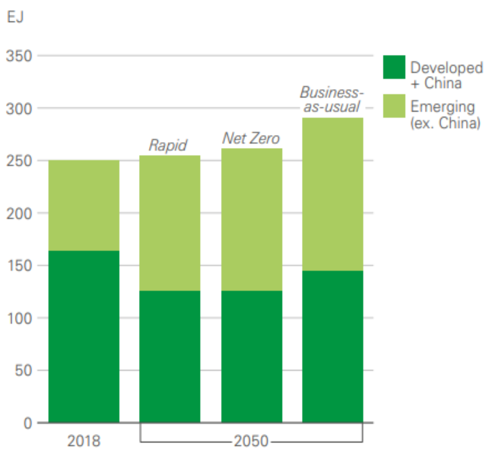

Figure 2 - Primary Energy Demand in industry according to various scenarios [2]

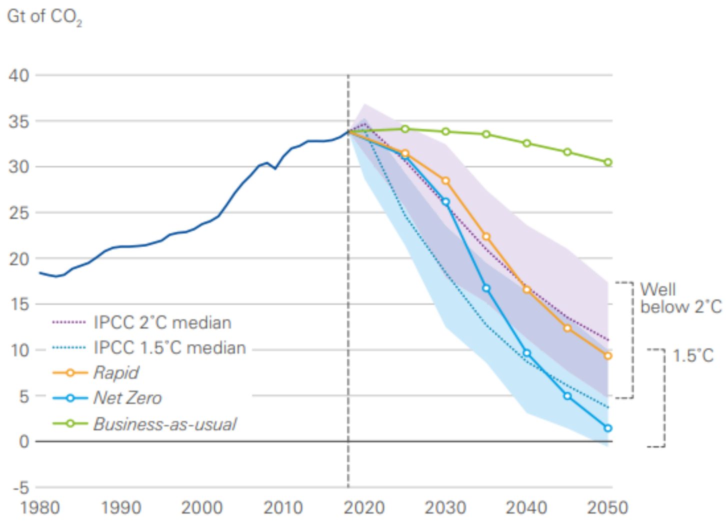

Figure 3 - Global Carbon Emission from energy use [2]

An important focus should be given to the emerging countries: in fact, they will contribute more and more to the growth in energy consumption and emission, as the most recent World Energy Outlook shows (figure 4), published by the International Energy Agency. In this case IEA considers the energy demand evolution according to a different scenario called Stated Policies Scenario (STEPS) that is similar to the BAU Scenario of the bp-Energy Outlook 2020.

This situation shows a positive trend of renewable that have a big share in the final demand. Unfortunately, by not taking drastic actions, fossil fuels will still account for a large share of the final demand.

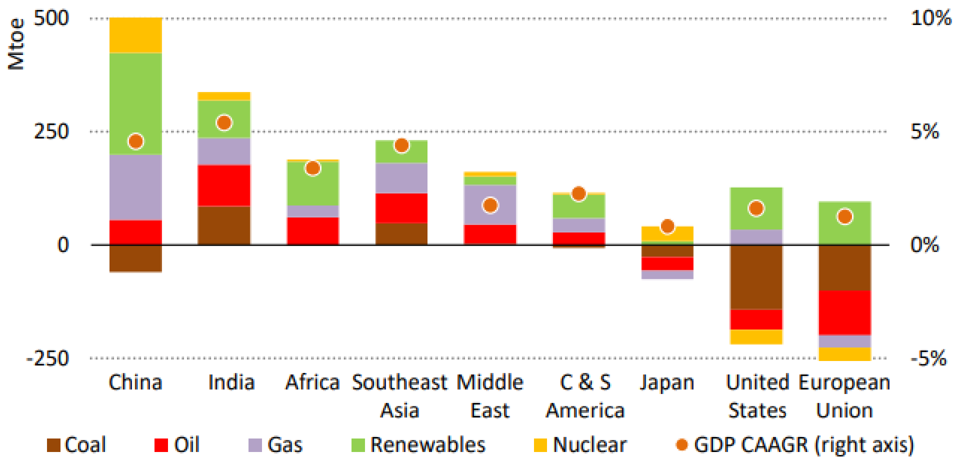

Figure 4 - changes in Primary Energy Demand by region and source between 2019 and 2030 [1]

Focusing more on industry, in a recent report [3] IEA shows how the industrial energy consumption is subdivided by sectors and what is the direct CO2 emission for each of them (figure 5).

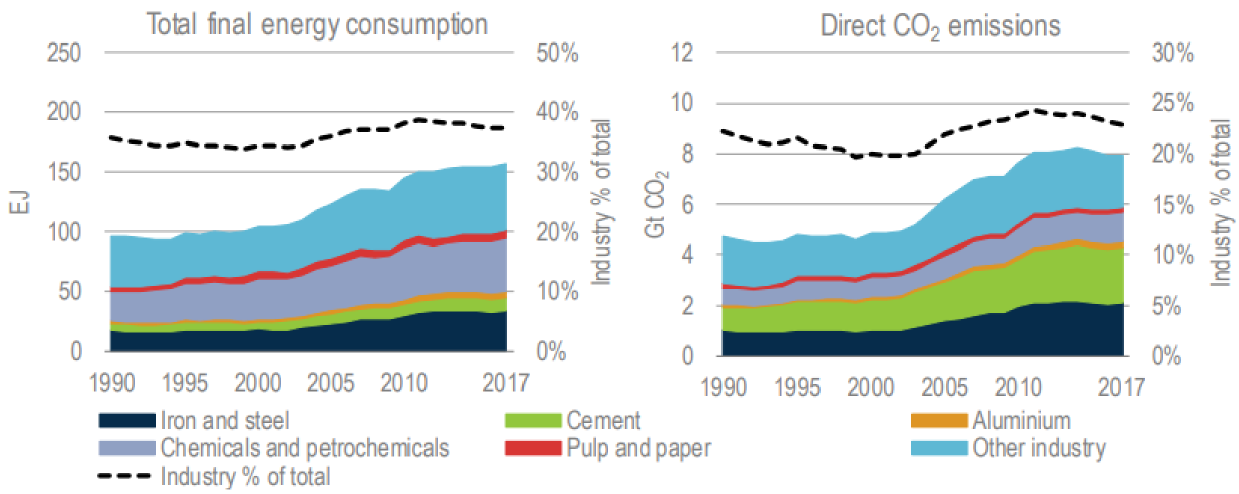

Figure 5 - energy consumption by industrial sector and related emissions [3]

It is interesting to notice that a high share of energy consumption (about 10% of the total final consumption) is related to the chemical and petrochemical industry, but this does not reflect on the direct CO2 emissions, since it has relatively low emissions compared to cement and metals industries. This could be explained by a lower use of fossil fuels in their process with respect to the other industries. A minor, but non negligible, effect on consumption and emissions is also related to the aluminium industry, that has grown rapidly in the recent years together with plastic [3] as shown in figure 6. This explains a noticeable growth for both in energy consumptions and emissions.

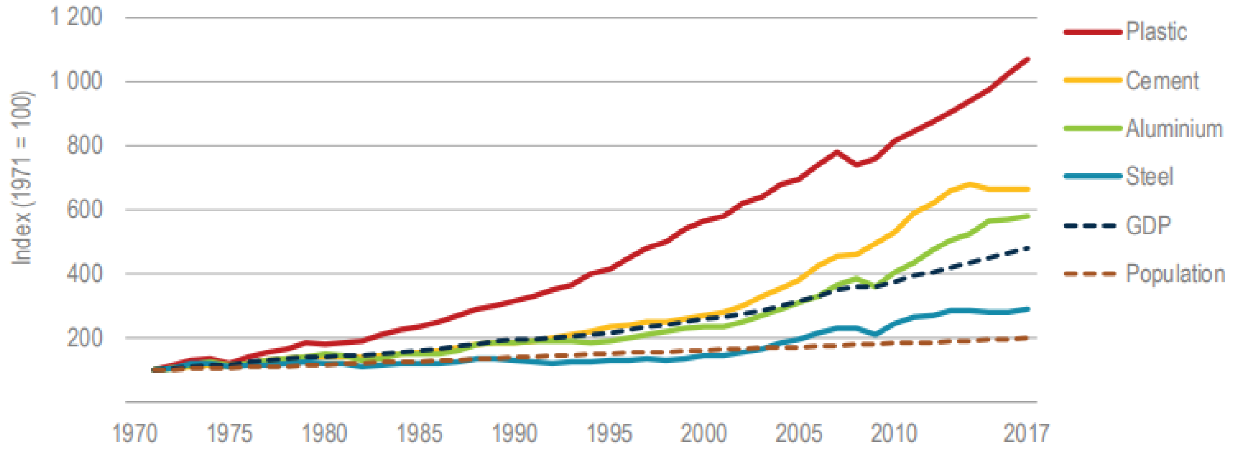

Figure 6 - demand growth for key materials, GDP, and population [3]

Usually in industries emissions are divided into categories called SCOPE. This methodology has been proposed through the GHG Protocol by the collaboration between the World Resources Institute (WRI), the World Business Council for Sustainable Development (WBCSD) and big industrial partners in order to quantify the company greenhouse gases in a standardized way [4]. SCOPEs are of three different types:

- SCOPE 1: it indicates all direct emissions generated by the factory and whose source is controlled by the factory itself. An example is the emission generated by fossil fuel burnt by a generator or by an industrial oven
- SCOPE 2: it regards all indirect emissions that are generated by energy purchased and consumed by the factory
- SCOPE 3: this category is related to the other indirect emissions that are generated through the value chain.

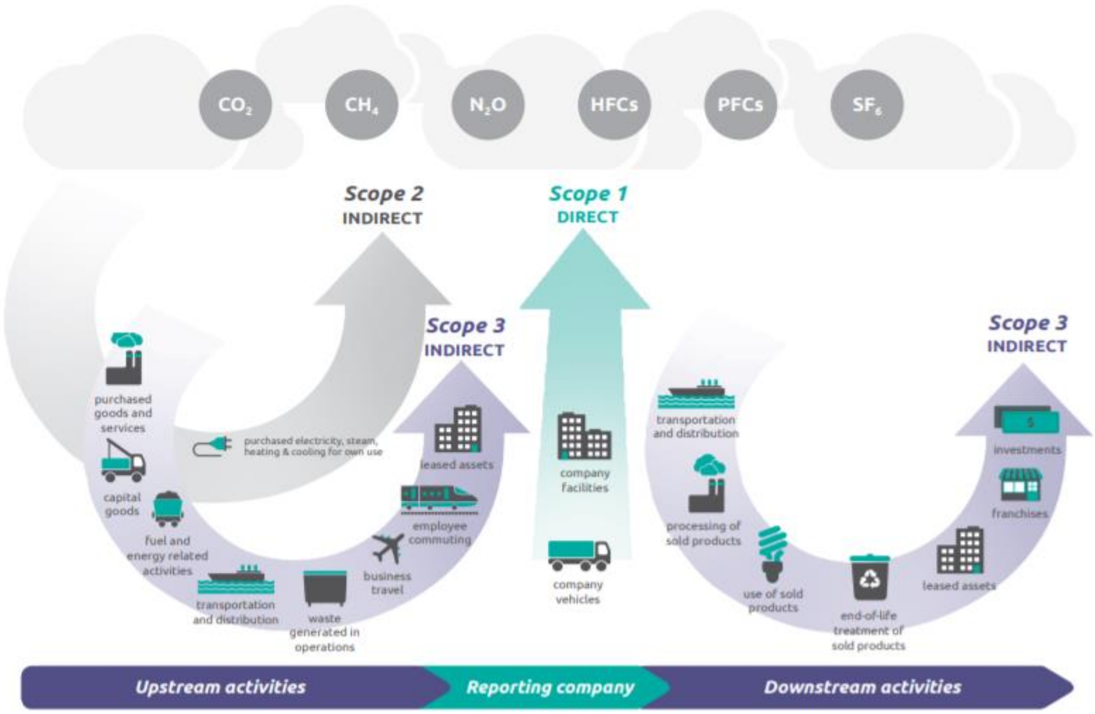

Figure 7 – Overview of the three scopes and the related activities [4]

For simplicity Scope 3 emissions will not be considered in this work since they are not strictly related to the industrial process. As established by the Kyoto Protocol, Scopes are calculated converting 6 greenhouse gases in equivalent CO2 emissions according to their global warming potential (table 1) [5].

GHG	*GWP*
Carbon dioxide CO_2	*1*
Sulfur hexafluoride SF_6	*24900*
Methane CH_4	*28*
Nitrous oxide N_2O	*265*
Hydrofluorocarbons HFCs	*Up to 11000*
Perfluorocarbons PFCs	*Up to 8200*

Table 1 - GWP of some GHG for 20-year time horizon [5]

Case study: Closures leader company

The presented case study concerns the assessment of partial decarbonisation of the industrial process of one or more closure factories of leader company. The first part aims at evaluating the performances of all factories, according to the emissions (SCOPEs) and the individual closure production, to choose the factories that will be studied more in depth and the justification behind the choice. It is done by calculating the specific emission for each factory and by comparing them according to the final product. The second part will focus on the industrial process in order to detect the weaknesses related to the emissions: in this case the required type of energy inputs is evaluated for each process step. The third part is related to the proposed technologies that the company could implement in the future in order to make the process more sustainable and their size. This is done by creating an algorithm in Excel that calculates how much the load is covered during each month, basing on the chosen technologies. The optimal PV size for each location is calculated using the software Homer Pro. The fourth part will focus on the techno-economic analysis by calculating the NPV for each factory and the final one will consider a sensitivity analysis on the various costs. All considered data in the following analysis are related to the year 2020.

Description of the company

The chosen company is a multinational leader of plastic and aluminium closures for spirits, wine, olive oil & condiments, water, and beverages in general. 28 factories over 5 continents produce every year tens of thousands of tons of closures, marketing its products in more than 100 countries.

Their factories are very diversified in the world, each of them with a particular industrial process. According to the factory, they can produce both plastic and aluminium closures or only one type of them.

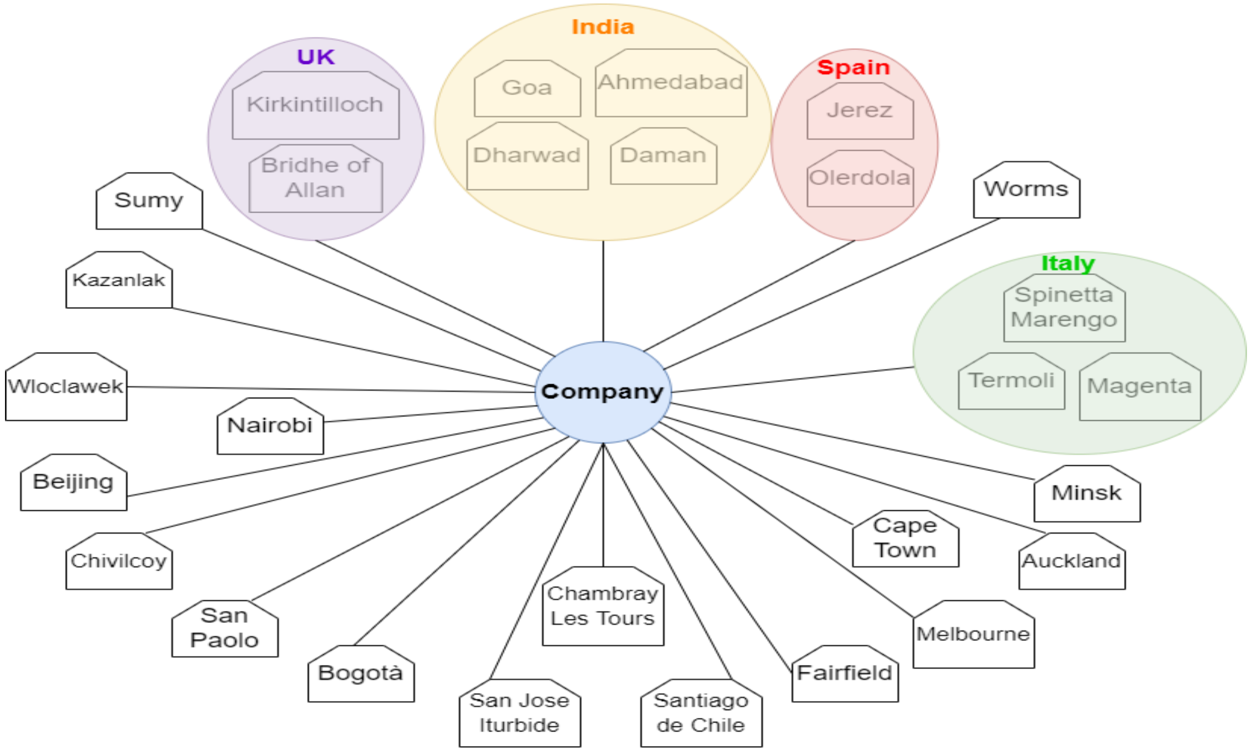

Figure 8 - Company factories around the world

Typology of factories

It is very important to know what type of closure the factory produces, since the industrial process changes between plastic and aluminium product and so do the input energy vectors.

The plastic cap production generally consumes more electricity for the injection presses and for cooling of mouldings. On the contrary, aluminium closure production requires more heat to decorate the final products. Factories are structured according to table 2:

Factory	*Typology*	*Country*
Spinetta	*AL+PL*	*Italy*
Termoli	*AL+PL*	*Italy*
San Jose Iturbide	*AL+PL*	*Mexico*
Sumy	*AL+PL*	*Ukraine*
Bridhe of Allan	*AL+PL*	*United Kingdom*
Kirkintilloch	*PL*	*United Kingdom*
Kazanlak	*PL*	*Bulgaria*
Beijing	*PL*	*China*
Goa	*PL*	*India*
Daman	*PL*	*India*
Ahmedabad	*PL*	*India*
San Paolo	*PL*	*Brazil*
Bogotà	*PL*	*Colombia*
Jerez	*PL*	*Spain*
Dharwad	*PL*	*India*
Nairobi	*PL*	*Kenya*
Magenta	*AL*	*Italy*
Wloclawek	*AL*	*Poland*
Santiago de Chile	*AL*	*Chile*
Fairfield	*AL*	*USA*
Melbourne	*AL*	*Australia*
Auckland	*AL*	*New Zeland*
Cape Town	*AL*	*South Africa*
Chambray-les-Tours	*AL*	*France*
Olerdola	*AL*	*Spain*
Chivilcoy	*AL*	*Argentina*
Minsk	*AL*	*Belarus*
Worms	*AL*	*Germany*

Table 2 - factories and materials that they process

It is important to say that the only factory that does not produce any closure is Magenta: actually, its main purpose is to produce and decorate aluminium sheets that will be exported to most of the company factories around the world.

Description of the process of plastic closures production

The process for producing plastic caps is quite similar in all the company factories as regards the various steps. Obviously, some steps may change according to the final product and may have different input energy vectors according to the machinery implemented to the process. Figure 9 summarises the process of plastic cap factories that has been simplified for an easier understanding.

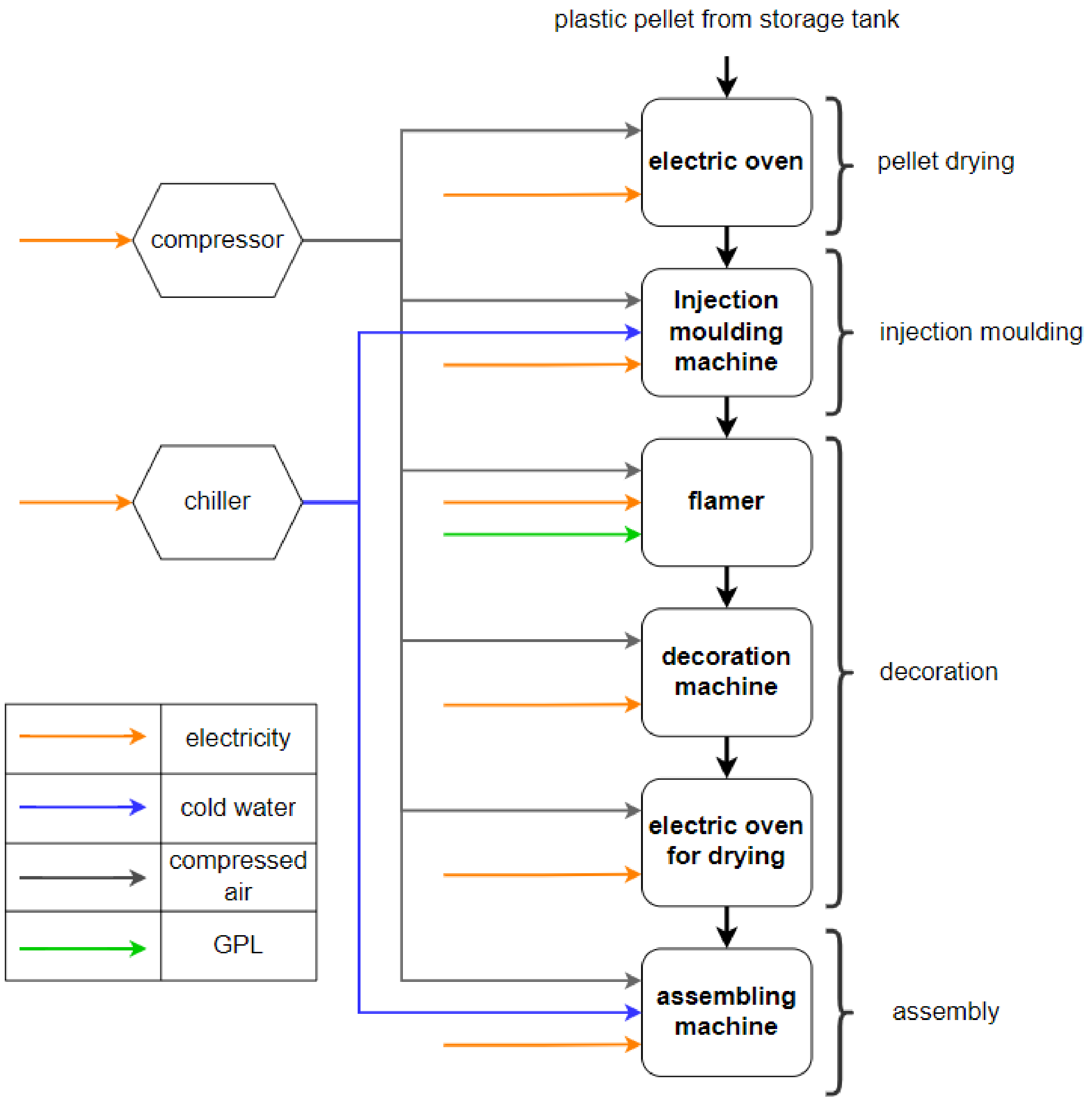

Figure 9 - plastic cap process and energy inputs

The entire process can be divided into 4 main steps:

- Pellet drying (optional, depending on the polymer): since moisture can affect the quality of the moulded caps, it must be removed from plastic pellet. This step is usually made through an electric oven, where hot air is injected and pellets are heated, releasing moisture.

- Injection moulding: as shown in figure 10, dried pellets are collected in a hopper that slowly releases them into a screw conveyor. During the carriage, pellets are heated through an electric winding around the conveyor in order to be molten. Molten plastic is then injected into a mold, cooled with cold water (usually 15°C) flowing in pipes inside the mold and finally ejected outside the machinery using compressed air and an ejector mechanism

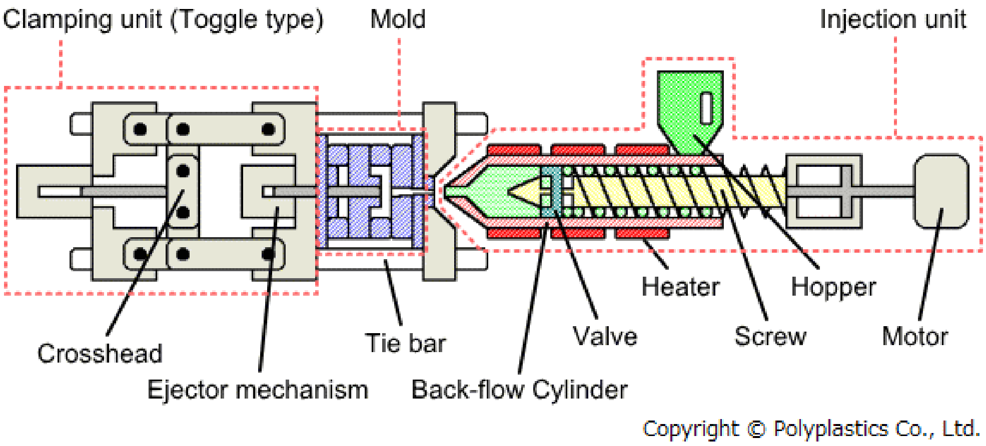

Figure 10 - example of injection moulding machine [43]

- Decoration: this step is optional, and it can be performed in very different ways according to the type of final product you want to obtain. Generally plastic closures pass through a flamer (for ex. in Indian factories it is GPL fuelled) to increase the surface wettability and to increase ink adhesion. Subsequently they are sent to the decoration machine that applies ink to the surface and enter to an electric oven to dry the fresh ink. The flamer and drying step are absent for UV and laser printing decoration
- Assembly: two or more plastic parts are assembled to produce the final product. Relatively cold water can be used to cool down assembly machineries

Figure 11 - example of plastic cap produced
in Indian factories

Differently from the plastic, the aluminium closure production process does not require the pellet drying and the injection moulding steps at the beginning, but it is characterised by the processing of aluminium sheets through the punching and the edging steps that give the desired shape to the closures.

Specific consumption for each stage greatly depends on the type of final product and the type of machineries used in the process. In order to give a quantitative idea, the specific consumption of some of various stages in an Italian factory (AL+PL) of the selected company is resumed in the table below (table 3).

Stages	*Specific consumption [kWh/t]*
Moulding + Decoration	*932*
Assembly	*291*
Compressed air production	*457*
Chiller + evaporative towers	*185*

Table 3 - indicative specific consumption in the process stages

Factory Performances

Specific energy consumption

In order to study the performance of a factory and to compare it with the others, its performance values should be normalized with the total final production. The first data of the analysis is the consumed energy, that has been calculated by considering the total electricity consumed by the entire factory plus the equivalent converted energy of all consumed fossil fuels.

The production is considered by taking into account the total tons of final product of each factory. The ratio between total consumed energy and tons of final product gives the results resumed in figure 12:

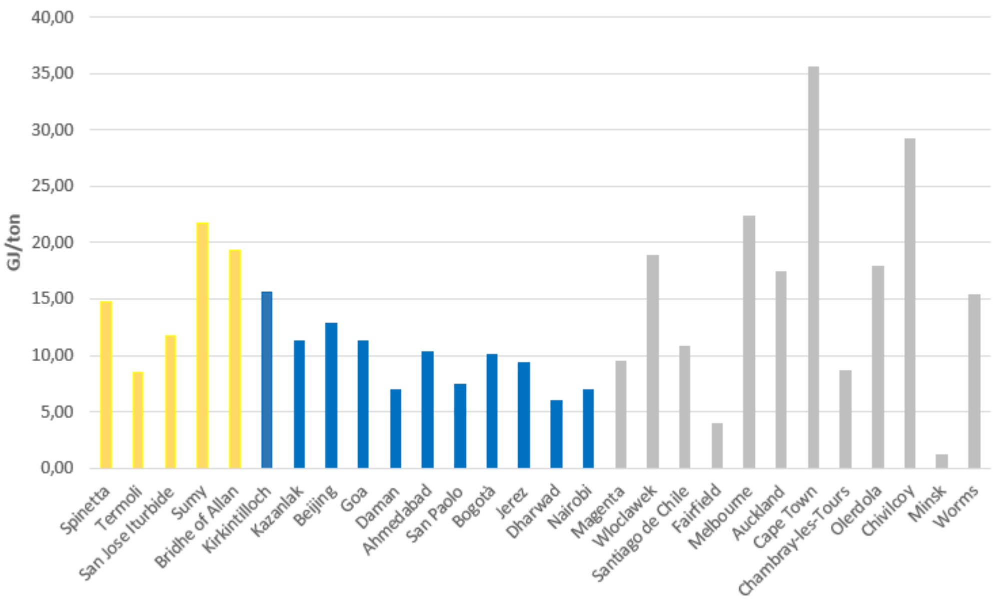

Figure 12 - total energy consumed by factory per unit of ton produced in 2020

Factories have been ordered in figure 12 as Table 1 from left to right, starting with AL+PL producers from Spinetta to Bridhe of Allan in yellow, then PL cap manufacturers are represented from Kirkintilloch to Nairobi in blue, and at the end AL closures factories from Magenta to Worms in grey. Statistically PL producers are the least energy consuming since their main consumption is electricity. On the contrary AL closures factories have a higher specific consumed energy values since there's a fundamental step in their process that requires fossil fuels to burn.

If we consider the share of electrical and thermal specific energy (figure 13,14,15), again we can easily detect the type of final product produced by each factory, for the same reason cited before, and see the predominance of thermal specific energy consumption in AL production and of electrical specific energy consumption in PL production.

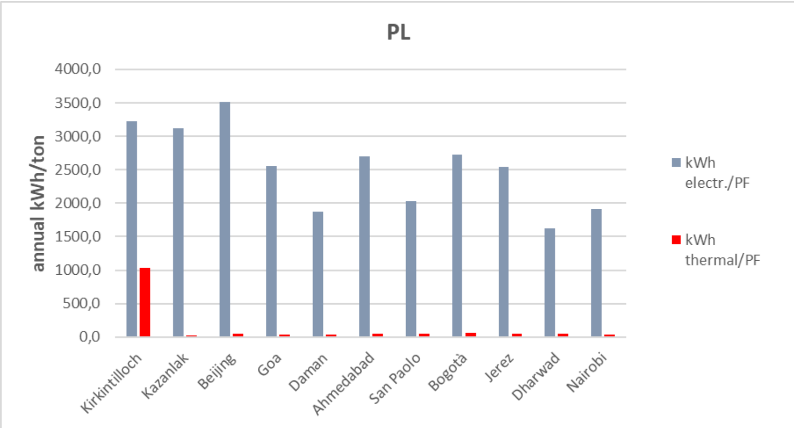

Figure 14 - share of thermal and electrical energy in PL factories

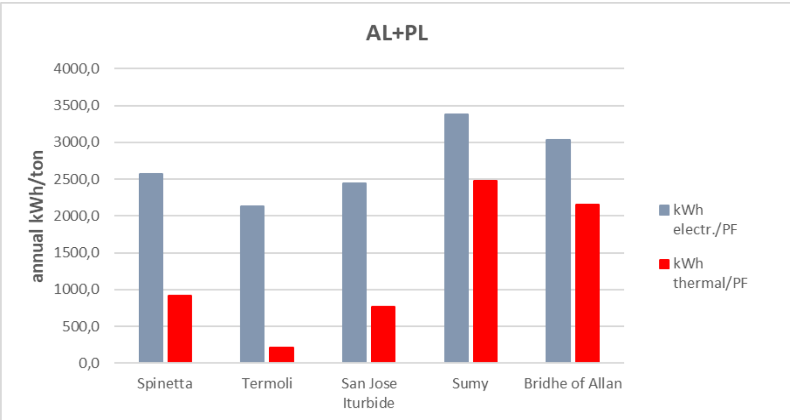

Figure 13 – share of thermal and electrical energy in AL + PL factories

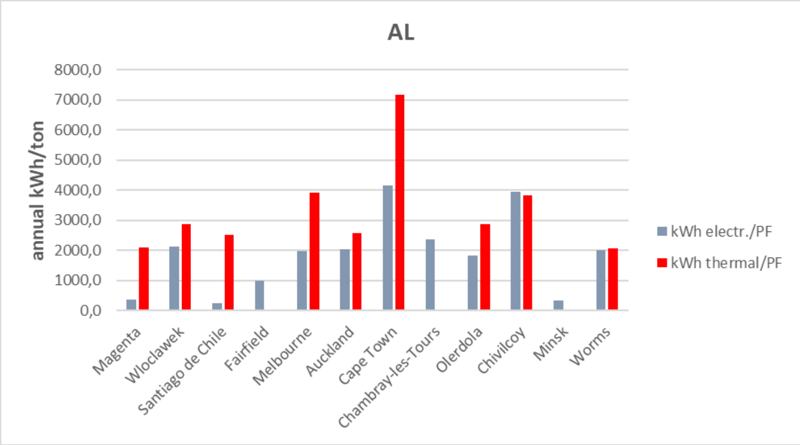

Figure 15 - share of thermal and electrical energy in AL factories

The efficiency of the various factories can also be represented by creating a scattered graph (figure 16) in which the ratio between energy consumption and tons of production reflects the angular coefficient of a representative straight line starting from the origin and passing through the point. The higher the angular coefficient, the lower the production efficiency. In the plot the two factories with the worst production efficiency are circled in red (Cape Town and Chivilcoy).

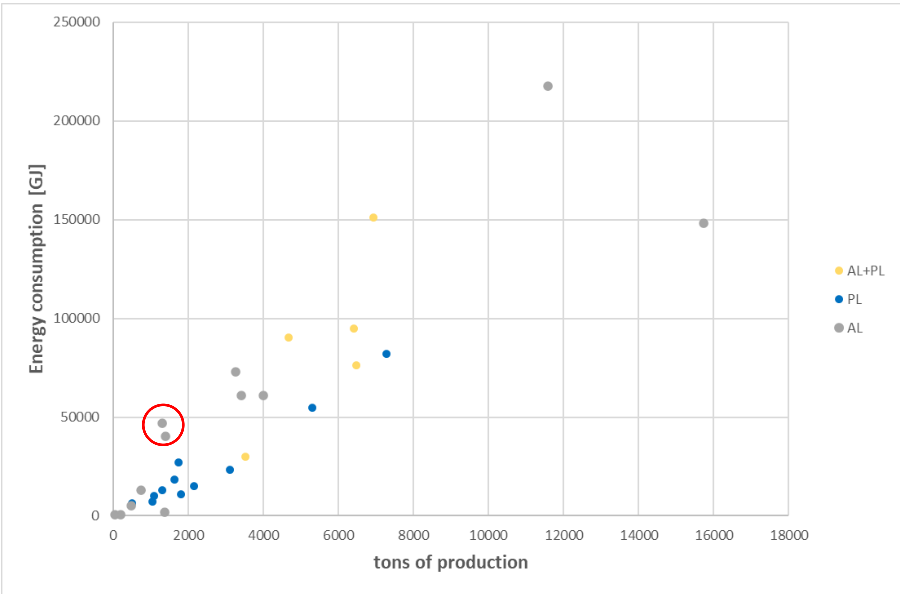

Figure 16 - process efficiency representation by type of final product

Emissions

Further interesting considerations on factories can be done if we look at the specific emissions of every factory. Figures 17,18 and 19 resume the share of tons of equivalent carbon dioxide emitted by each factory for Scope 1 & 2 normalized with respect to the produced tons of closures.

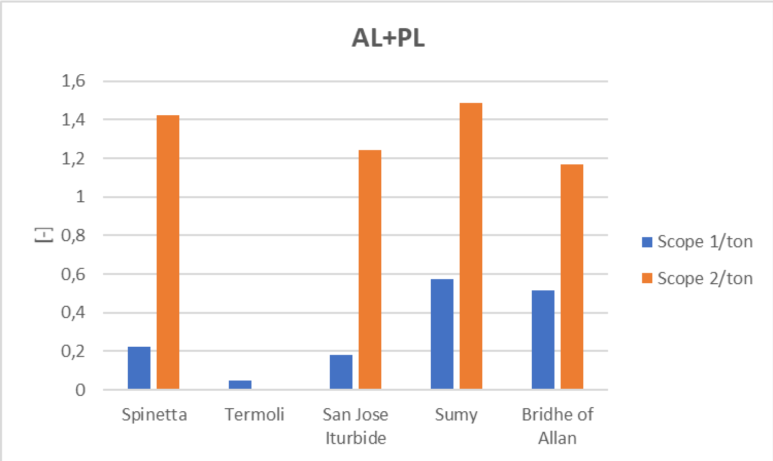

Figure 18 - share of SCOPE 1 & 2 for AL+PL factories

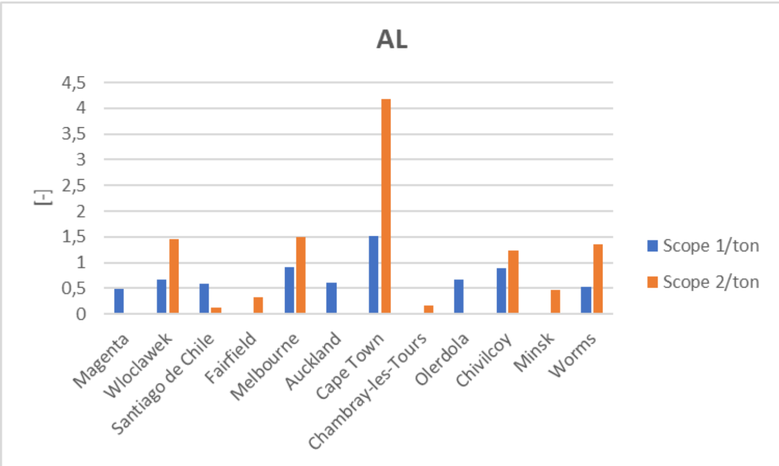

Figure 17 - share of SCOPE 1 & 2 for AL factories

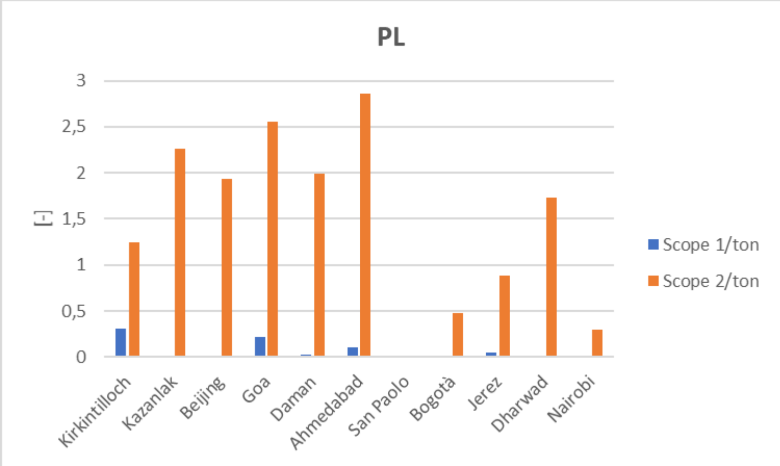

Figure 19 - share of SCOPE 1 & 2 for PL factories

As stated before, aluminium closures require a hot source in the production process, usually between 150 °C and 180 °C. This source is usually generated through fossil fuel burning and this is very well reflected in the emission share: since it accounts in Scope 1 emissions, AL producer factories have a considerable percentage of this kind of emissions, while it is often negligible in PL ones. These graphs also reflect an important concept: most of the emissions are related to Scope 2 and on average they account for 70% of total emissions of Scope 1 & 2. This suggests that a goal to decarbonise the process of most of these factories is to consume energy that is directly produced by renewable sources. This goal has already been undertaken by Termoli, Magenta, Olerdola, Auckland and San Paolo factories, since they started to buy 100% electrical energy by renewable technologies from the beginning of 2020: it explains the almost null Scope 2 in the graph above.

Another interesting consideration can be done by focusing on figure 20: on average PL factories are distinguished by slightly higher specific emission, mainly due to their high electricity consumption as seen before.

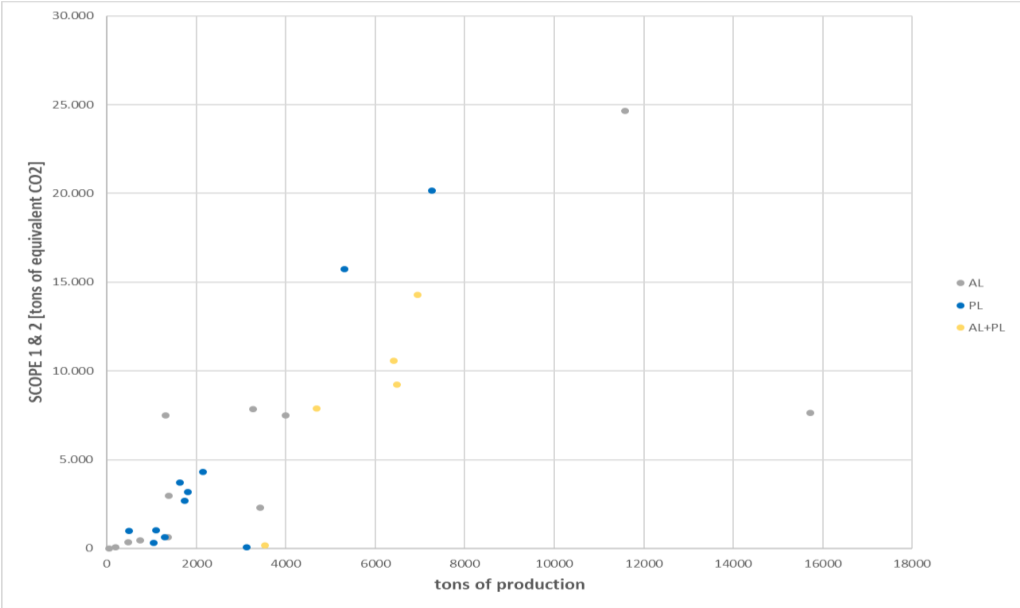

Figure 20 - specific emissions by type of final product

Figure 21 resumes the total specific emission by including all the factories on the same plot. In this case too Cape Town shows the worst specific emission factor. Apart from it, all factories in India (Goa, Ahmedabad, Daman and Dharwad) show low efficiency in terms of emissions. Therefore, based on these results, the following chapters will focus on Indian factories and the suggestion of some renewable technology implementations in the process to try to partially decarbonize the industrial process.

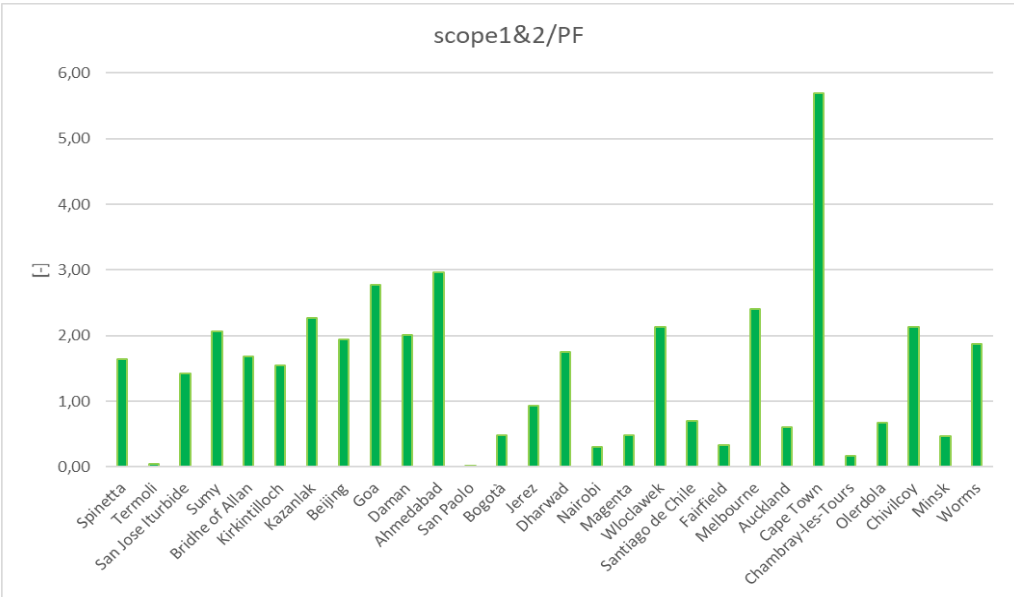

Figure 21 - sum of specific emissions by factory

Technology proposal

The chosen Indian locations are characterised by a good solar irradiation, as shown in the next chapter. Unfortunately, the same doesn't go for wind, since the wind speed at medium heights (50 meters) ranges between 4 and 5 m/s according to Global Wind Atlas [6], too low values for wind power to be convenient. Moreover, there aren't renewable resources in the nearby locations to be exploited during the night since all locations are far from geothermal sources or from the sea. According to these environmental limitations and the almost 100% requirement of electrical energy by the factories, the proposed technologies to implement in the process are the following:

- photovoltaic system on the rooftop of each industry + a ground mounted photovoltaic system at commercial scale (between 0.5 and 7 MW) and a Li-ion battery
- Proton-exchange membrane fuel cell (PEMFC) and Proton-exchange membrane electrolyser (PEMEC) + hydrogen storage system.

The purpose of the system is to produce energy through PV panels to cover the load during the daytime. The excess of energy will be used to charge the Li-ion battery and, when fully charged, electricity will be exploited in a PEM electrolyser to produce green hydrogen. Then, the gas will be compressed, cooled down and stored in above ground pressure vessels. During night-time, when PV modules do not produce any energy, the battery will be discharged and, when fully discharged, the stored hydrogen will flow in a PEM fuel cell to cover the load.

These technologies are proposed to be implemented starting from 2030. PV is already a very mature technology but the same doesn't go for PEM technologies, which are a relatively new concept and not economically convenient yet. Their costs are expected to decrease in the future due to the learning effects and economies of scale as stated by Cigolotti et al. (2021) [7] and von Leeuwen et al. (2018) [8] as shown for example in figure 22 for the fuel cell, together with an improvement in performances [9] [10].

Therefore, the whole system is proposed starting from 2030, where a strong reduction in PEM prices is expected.

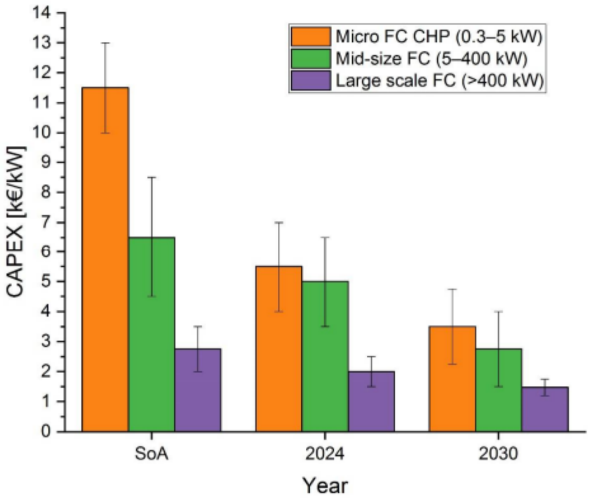

Figure 22 - CAPEX forecast of FC [7]

Photovoltaic system

India can be considered a "lucky country" since it is characterized by a relatively high global horizontal solar irradiation in most of its territories, ranging between 1800 and 2000 kWh/m^2 and therefore a good specific solar yield [11]. Furthermore, the four considered factories lay in the west side of India where climate is hot and tropical, and temperatures rarely decrease below 18 °C [12]. Unfortunately, high temperatures can be a disadvantage for PV panels, since their overheating above a reference value leads to a decrease in electrical efficiency and therefore to power production.

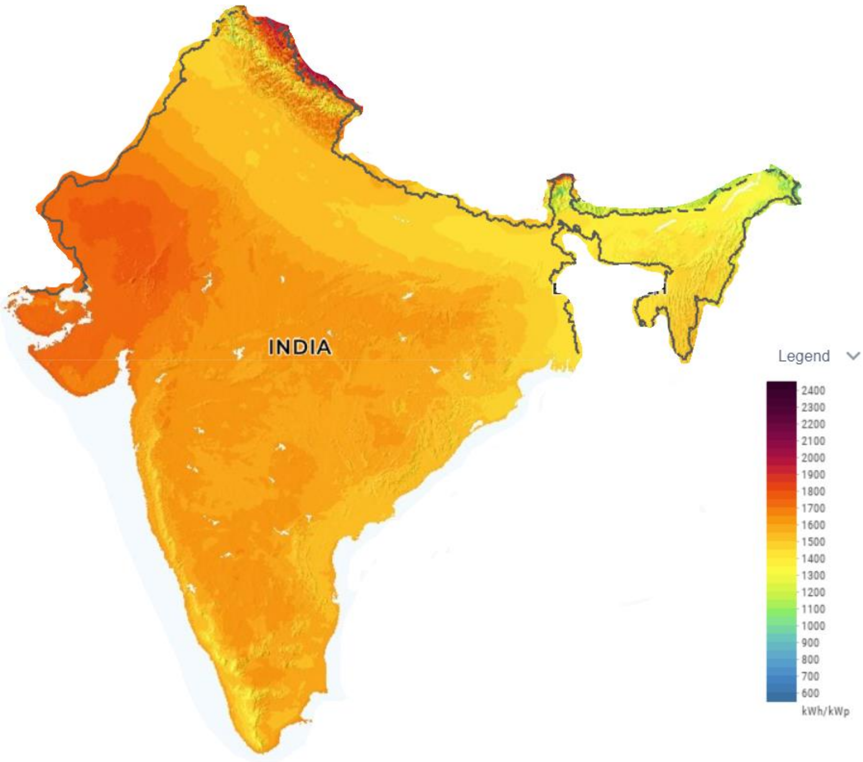

Figure 23 - solar yield in India [11]

Solar radiation by Indian location

Figures 25, 26, 27 and 28 resume the solar radiation and its hourly evolution for a typical day of the month.

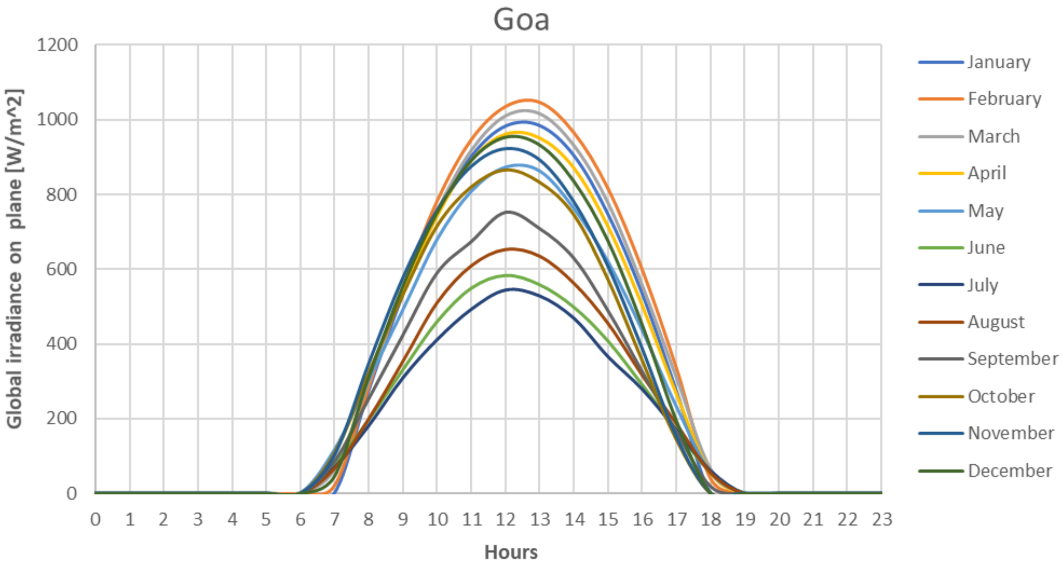

Figure 25 - hourly solar irradiation by month in Goa [18]

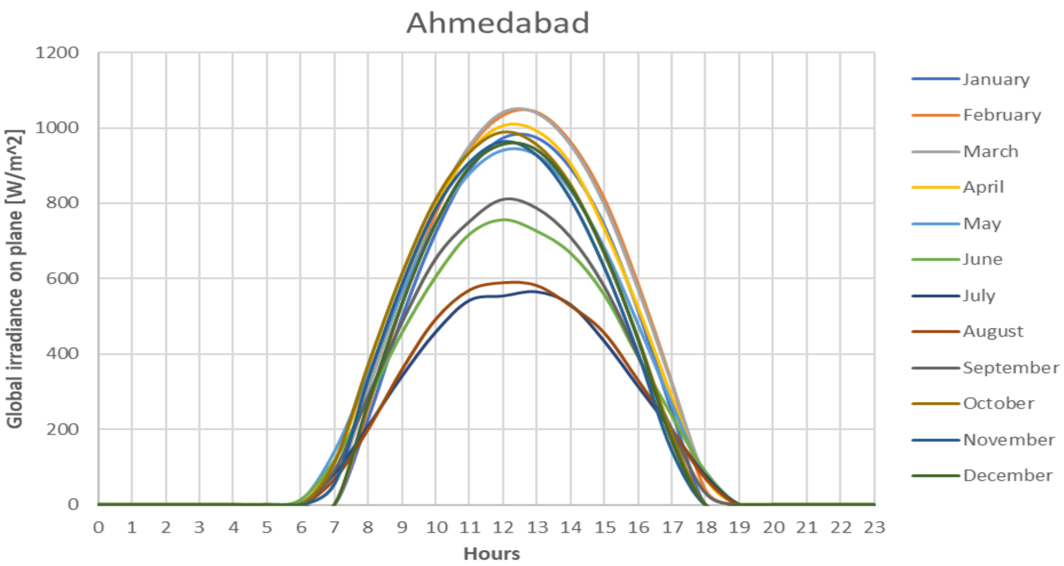

Figure 24 - hourly solar irradiation by month in Ahmedabad [18]

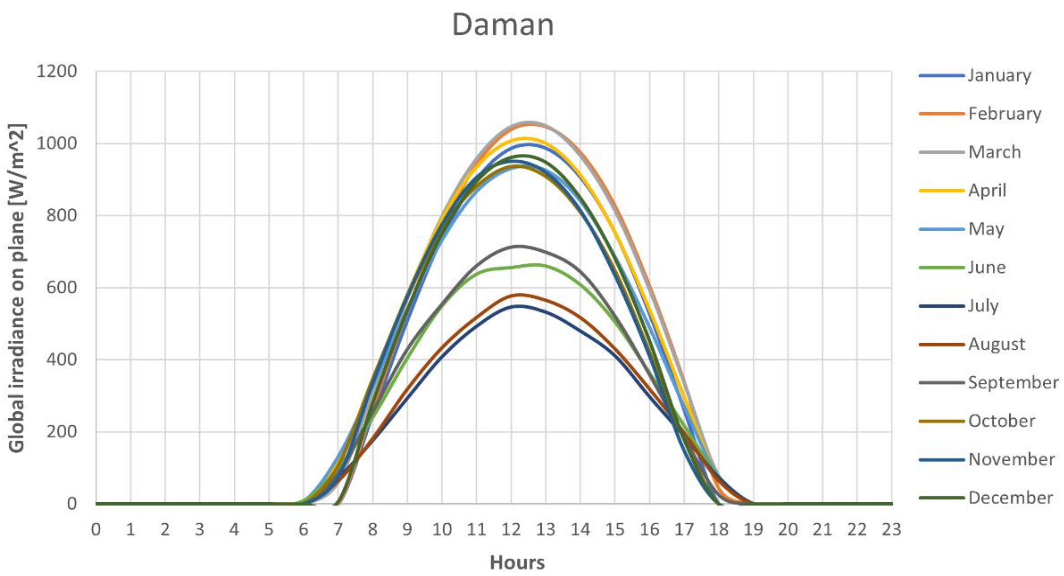

Figure 26 - hourly solar irradiation by month in Daman [18]

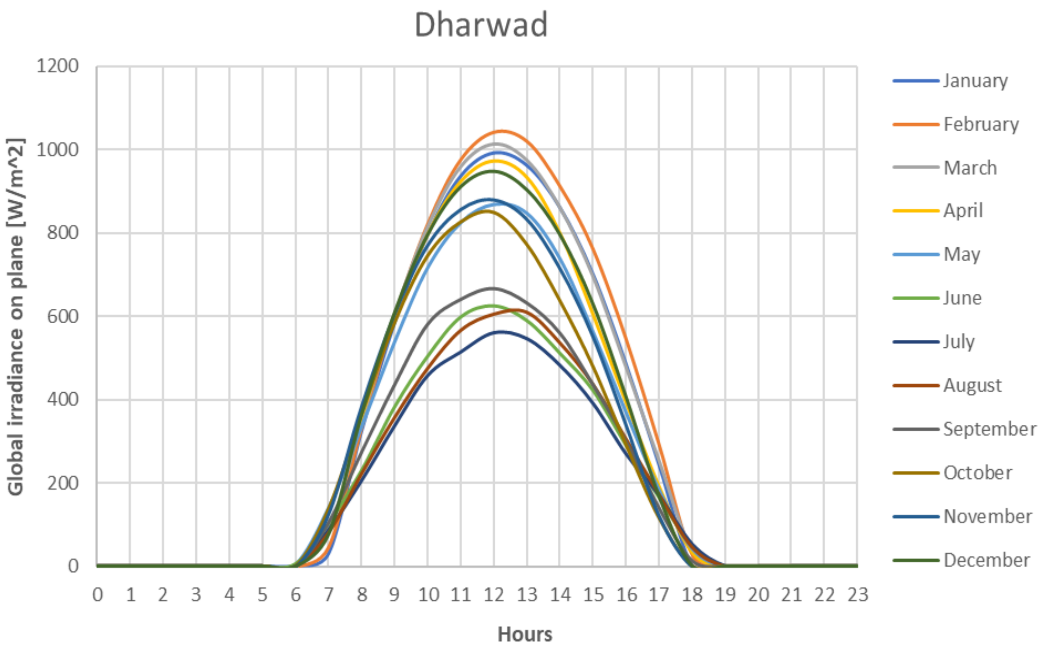

Figure 27 - hourly solar irradiation by month in Dharwad [18]

The trend is similar in all locations: irradiation is similar for each month, varying from 900 to over 1000 W/m^2, except between June and September, where it drops between 500 and 600 W/m^2: this can be explained since it is the Monsoon period in India [13] and heavy rains occur all over it, decreasing the average solar irradiation. For this reason, the main challenge will be to cover the load with renewables and lower the emissions in the Monsoon period.

PV and Battery Technical aspects

In the last ten years, the average efficiency of commercial photovoltaic panels has grown from 15% to 20%. Recently, higher values have been obtained at laboratory scale for monocrystalline panels (26,7%) and for polycrystalline ones (24,4%) [13], and further research will hopefully increase the performances. For the analysis, a monocrystalline PV has been considered both for the roof and ground since it has higher efficiency with respect to polycrystalline silicon. The technical characteristics are reported in table 4.

Model	*Manufacturer*	*Type of PV*	*Peak power of the module*	*Efficiency*	*Area of the module*	*T coefficient of power*	*Lifespan*
WSM-315	*Waaree*	*Monocr.*	*315 W*	*19.81%*	*1.664 m^2*	*-0.37%*	*25*

Table 4 - Technical features of PV panel [14]

The chosen PV panel is manufactured by Waaree, one of the biggest solar companies in India [15].

Aging is a phenomenon that negatively affects optical and electrical properties and leads to a decrease of the productivity. In this work it won't be taken into consideration, but for completeness its performance warranty represented in the datasheet is reported in the following table:

	After 1st year	*From 2nd year*
Waaree	*3%*	*0.7%*

Table 5 - PV performance warranty [14]

The maximum number of modules that can be installed on the rooftop of each factory has been evaluated by dividing the total area of the roof to the area of a single PV module (table 6). For simplicity and for lack of information, factory roofs are considered flat surfaces. Moreover, a structural analysis of the roof would be necessary, but, since it exceeds the topic of this work, roofs are considered to be able to withstand the weight of such number of PV module.

	Goa	*Ahmedabad*	*Daman*	*Dharwad*
Total roof area [m^2]	*2700*	*8000*	*2300*	*3000*
N° of modules	*1622*	*4807*	*1382*	*1802*
Max Installed capacity on the roof [kW]	*511*	*1514*	*435*	*568*

Table 6 – PV roof characteristics by location

Concerning the ground mounted PV, from Google Maps potential nearby lands have been detected for each factory where ground mounted PV could be installed. For complexity reasons no further analysis on land restriction has been undertaken and therefore they will be considered buildable.

Using as input for Homer Pro the costs proposed in the techno-economic part, the optimal PV sizes are found, separated in ground and roof PV capacities and used as input in the Excel algorithm. If the optimal size is higher than the maximum one on the roof, the excess of power will be installed on the ground (table 7). To evaluate the value of the occupied area the US land use requirement for solar plants [16] is considered, stating that usually a total area of 7.6 acres is required for each MW of fixed PV.

	Goa	*Ahmedabad*	*Daman*	*Dharwad*
Optimal Homer Pro PV size [kW]	*4380*	*4900*	*805*	*1055*
Installed PV capacity on the roof [kW]	*511*	*1514*	*435*	*568*
Installed PV capacity on the ground [kW]	*3869*	*3386*	*370*	*487*

Table 7 - values of PV installed capacity

Concerning the Li-ion battery, the capacity is initially chosen to satisfy one hour of the peak load and resumed in table 8. Its lifetime is assumed to be 10 years and its minimum state of charge (SOC) equal to 20%.

	Goa	*Ahmedabad*	*Daman*	*Dharwad*
Battery Capacity [kWh]	*2808*	*2221*	*601*	*479*

Table 8 - Li-ion Battery technical aspects

PV Productivity

Once the type of photovoltaic panel has been chosen, its productivity must be calculated. Its power output is evaluated according to the following equation [17]:

$$P_{PV-out,DC} = P_{PV-nominal} \cdot \left(\frac{G}{G_{ref}}\right) \cdot \left[1 + k_T\left(T_C - T_{ref}\right)\right] \cdot \frac{1}{1000}\ [kW] \qquad (1)$$

Where $P_{PV\text{-}nominal}$ is the nominal power of the PV module at STC, G is the global irradiance (W/m^2) of the chosen location, G_{ref} is the solar irradiance at reference conditions and it's equal to 1000 W/m^2, k_T is the temperature coefficient of power (%/°C), T_{ref} is the cell temperature at reference conditions (T_{ref}=25°C). T_C is the cell temperature of the actual conditions, and it can be approximated as [17]:

$$T_C = T_{ambient} + (0.0256 \cdot G)\ [°C] \qquad (2)$$

where $T_{ambient}$ is the air temperature of the location at 2-meters. PV modules produce electricity as direct current; therefore, an inverter is fundamental to convert it in alternate current to satisfy the factory load. Hence equation (1) must be multiplied by the inverter efficiency η_{inv} whose value is assumed equal to 95%. The final equation of PV power in AC is the following:

$$P_{PV-out,AC} = P_{PV-out,DC} \cdot \eta_{inv}\ [kW] \qquad (3)$$

Solar irradiance and air temperature values have been obtained from PVGIS, an online free solar photovoltaic calculator [18], for each of the considered locations. Hourly data of a typical day have been extracted for each month of the year, considering the optimal tilt angle and plane orientation for each place (table 9) through the same calculator.

	Goa	Ahmedabad	Daman	Dharwad
Optimal tilt angle [°]	*21*	*27*	*25*	*21*
Optimal plane orientation [°]	*2*	*-1*	*2*	*-5*

Table 9 - optimal angles by location [18]

PEMFC/PEMEC technical aspects

There are three main types of fuel cells and electrolysers nowadays, divided according to the type of electrolyte: the Alkaline, the Proton-Exchange Membrane and the Solid Oxide ones. PEM electrolysers and PEMFC have been chosen because of their quick start-up [7] [8], a fundamental characteristic when the switch between the two must occur within an hour. For the same reason, since fast withdrawal and injection rates are required, pressure vessels are chosen to store the gas. At first the electrolyser nominal power is evaluated according to the maximum value of excess of energy when the battery is fully charged in the months not affected by Monsoons. This is done because in this period the excess of energy is very low or null and so hydrogen production is absent. Consequently to the electrolyser capacity, the fuel cell nominal power is selected according to the maximum power it would be able to satisfy with the stored hydrogen. The choice of the hydrogen storage capacity depends on how much hydrogen the electrolyser is able to generate during the day. A first assumption is done by calculating the remaining excess of energy after the battery fully charging and using the formulas shown in the following chapter to calculate the hydrogen production. It is then summed up until there's an energy deficit. This is done for a representative day of each month and the highest value is chosen as hydrogen capacity.

The nominal power of the hydrogen compressor is determined with the formula in the next chapter (eq. 12) after choosing the two previous data so that its size is able to compress the maximum hydrogen flowrate produced by the electrolyser. Starting from an inlet pressure of 30 bar from the electrolysis (typical value of PEMEC [19]), a compression ratio of 10 is considered (outlet pressure equal to 300 bar) in order to have a good compromise between specific energy stored, energy consumed by the compressor and cost of the tank. Table 10 shows the selected parameters for each location.

	PEMFC [kW]	PEMEC [kW]	Storage capacity [kg] at 300 bar	Compressor nominal power [kW]
Goa	*1740*	*2027*	*169*	*56*
Ahmedabad	*2221*	*2464*	*235*	*68*
Daman	*238*	*291*	*18*	*9*
Dharwad	*470*	*553*	*53*	*16*

Table 10 – selected nominal power and capacity of machineries by location

PEMEC productivity

The excess of energy produced by photovoltaic panels feeds the electrolyser to produce hydrogen. Basing on [20], the formula to calculate the gas flowrate produced by the PEMEC is evaluated starting from the specific consumption of the electrolyser. As we know, SC is the ratio between the energy input E_{in} in kWh and the normalized cubic meters of hydrogen V_{H2} (eq. 4).

$$SC = \frac{E_{in}}{V_{H2}} \left[\frac{kWh}{Nm^3_{H2}}\right] \qquad (4)$$

It can also be written as the electrical power over the hydrogen volume flow (eq. 5).

$$SC = \frac{W_{el}}{\dot{V}_{H2}} \left[\frac{kWh}{Nm^3_{H2}}\right] \qquad (5)$$

In the electrolyser volume flow is expressed as (6):

$$\dot{V}_{H2} = \frac{i \cdot S}{2F} \cdot n_c \cdot V_{mol,H2} \cdot \frac{1}{3600} \quad \left[\frac{Nm^3_{H2}}{h}\right] \qquad (6)$$

Where:

- i is the current density of the cell [A/cm^2]
- S is the cell surface [cm^2]
- F is the faraday constant (corresponding to 96847 [C/mol])
- n_c is the number of cells
- $V_{mol,H2}$ is the volume per mole of hydrogen (equal to 0,0224 [m^3/mol])

Moreover, the power can be rewritten as (7):

$$W_{el} = \frac{n_C \cdot V_C \cdot I}{1000} \quad [kW] \qquad (7)$$

In eq. (7) I corresponds to the total current [A] and V_C to the single cell voltage [V].

Substituting (6) and (7) in (5) and simplifying the same terms, we obtain the following equation for specific consumption:

$$SC = \frac{3600}{1000} \cdot \frac{V_C}{V_{mol}/_{2F}} \qquad (8)$$

Since V_{mol} and F are constant, (8) reduces to a simple equation:

$$SC = 2.44 \cdot V_C \quad \left[\frac{kWh}{Nm^3_{H2}}\right] \qquad (9)$$

Eq. (9) implies a direct relation between SC and the cell voltage and, since V_C is a function of the current density (and so of the point of operation of the electrolyser), SC will change accordingly. Figure 28 shows a typical electrolyser behaviour as the current density changes.

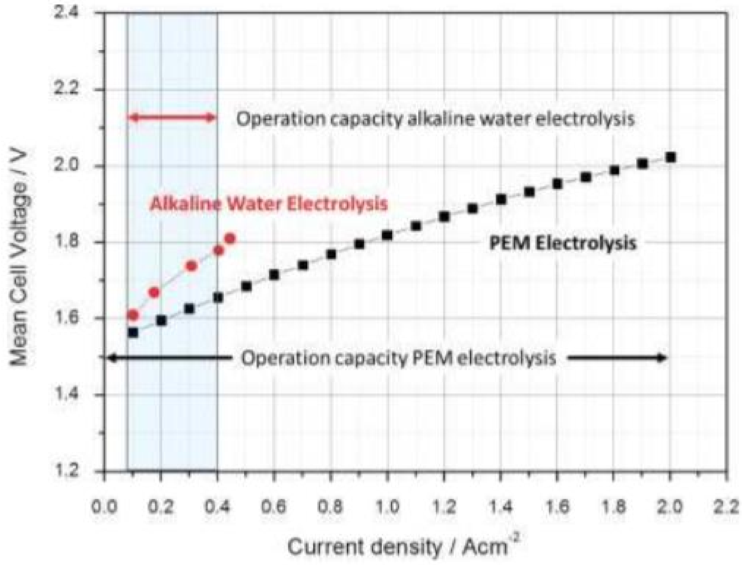

Figure 28 - typical voltage-current behaviour of two types of electrolysers [44]

In this work, since the precise technical characteristics of the chosen electrolyser are not known, the cell voltage has been considered as an average constant value that is typical for PEMEC [21].

Equation (9) is converted from kWh/Nm^3 to kWh/kg$_{H2}$ by simply multiplying it with the volume of a gas mole at normal conditions (that is equal to 22,4 litres per mole) and dividing it for the molar weight of hydrogen. Finally, the hydrogen mass flow rate can be calculated (eq. 10) by dividing W_{excess} with SC, where W_{excess} is calculated as eq. (11) and considers the difference between the power required by the factory and the power of solar PV panels when the battery is already fully charged.

$$\dot{G}_{H2}[\frac{kg}{h}] = W_{excess}[kW] \cdot \frac{1}{SC} [\frac{kg}{kWh}] \quad (10)$$

$$W_{excess} = (W_{load} - W_{PV,roof,AC} - W_{PV,ground,AC}) \cdot (1-f) \cdot \frac{1}{\eta_{inv}} \quad [kW] \; (11)$$

The excess of power must be divided by the inverter efficiency, since PEMEC is fed by direct current.

Since hydrogen must be compressed in a compressor to be stored, not all the excess of energy can be absorbed by the electrolyser, but a fraction (parameter f in (11)) must feed the compressor. The value of f is strictly related to the mass-flow rate produced by the PEMEC and it is calculated iteratively. The compressor power required to compress the gas generated by the PEMEC is calculated according to eq. (12) [22].

$$W_{compr} = Q \cdot \frac{Z \cdot T \cdot R}{\overline{M_{H2}} \cdot \eta_{compr}} \cdot \frac{N \cdot \gamma}{\gamma - 1} \cdot \left[\left(\frac{p_{out}}{p_{in}}\right)^{\frac{\gamma-1}{N \cdot \gamma}} - 1 \right] \quad [kW] \quad (12)$$

Where:

- Z: hydrogen compress. Factor =1 (approx.)

- R: ideal gas constant = 8.314 J/(K*mol)
- T: temperature at inlet =278 K
- γ: diatomic constant factor = 1.4
- N: compressor stage number
- η_{compr}: compressor efficiency =75%
- $\overline{M_{H2}}$: hydrogen molecular mass = 2.016 g/mol
- p_{in}: pressure inlet = 30 bar
- p_{out}: pressure outlet = 300 bar
- Q: mass flow-rate

Table 11 resumes the cell voltage, the Specific Consumption SC and the fraction of energy to the compressor used for all the locations.

Parameter	*Assumed values*
Cell voltage [V]	*1.7*
SC [kWh/kg]	*50.2*
f [%]	*2.76*

Table 11 - characteristics of PEMEC consumption

Together with electricity, the main input of the PEMEC is water. The required quantity of water to produce one kilogram of hydrogen can be calculated approximately by considering the water splitting reaction (13).

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \qquad (13)$$

Water and hydrogen molar masses are respectively 18 g/mol and 2 g/mol. This means that to produce 1 kg of hydrogen, 9 kg of water are required.

PEMFC productivity

When the excess of power goes below the required load and battery is discharged, PEM fuel cell is "switched on" and fed with hydrogen from inside the tank. PEMFC must therefore cover the difference between the load and the energy produced by PV. Basing on [23], equation (14) is used to calculate the necessary mass-flow rate. When the remaining stored hydrogen cannot satisfy the load, it is fully discharged and electricity from the grid must be necessarily purchased (eq.15).

$$\dot{G}_{H2} = \frac{W_{load} - W_{PV,roof,AC} - W_{PV,ground,AC}}{V_C} \cdot \lambda_{H2} \cdot \frac{1}{2F} \cdot \bar{M}_{H2} \left[\frac{kg}{s}\right] \qquad (14)$$

$$W_{purchased} = W_{load} - W_{PV,roof,AC} - W_{PV,ground,AC} - \dot{G}_{H2} \cdot V_C \cdot \frac{2F}{\lambda_{H2} \cdot \bar{M}_{H2}} \cdot \eta_{inv} \; [kW] \qquad (15)$$

Since in a fuel cell we need to be sure that all the hydrogen at the inlet reaches the reaction zones at the cathode, the inlet mass-flow rate must be in excess compared to the stoichiometric value. This is taken into account in eq. (14) and eq. (15) by λ_{H2} that represents the excess of hydrogen. Its value is usually considered equal to 1.2 (20% of excess of hydrogen) for PEMFC [23]. This excess will be present together with reaction products at the outlet: therefore, it is usually recovered by treating outlet water and re-injecting the gas at the inlet. The other terms in eq. (14) and (15) are:

- Hydrogen molar mass $\overline{M}_{H2}$ = 2.016 [g/mol]
- Faraday constant F = 96487 [C/mol]
- V_C is the single cell voltage, for a PEMFC it usually varies between 0.7 and 0.9 V [24] [25] [26] and it is a function of the cell current.

In this work, since FC mostly works at nominal value, the cell voltage is considered equal to 0.8 V. An analogue comment can be done for oxygen at the cathode inlet. An excess of O_2 is required for the reaction because it brings to two main benefits: it improves the stack voltage at high current densities (figure 29), and it carries out the accumulated mass of water at the cathode that would inhibit the electrochemical reaction [27]. It is taken into account in the inlet air flowrate calculation (eq. 16) through the parameter λ_{air}.

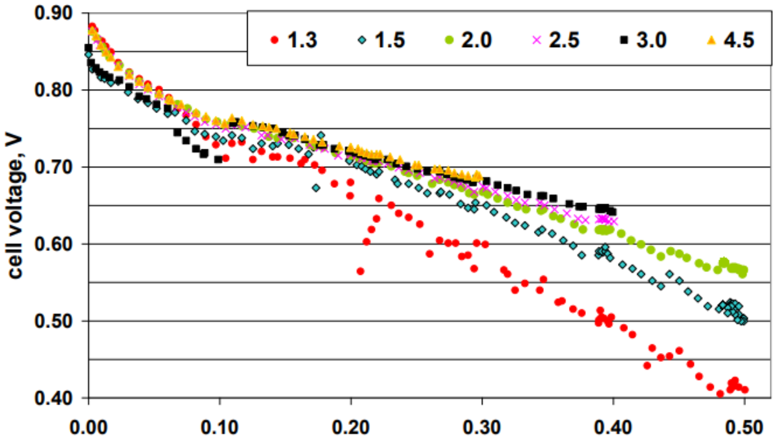

Figure 29 - influence of air excess in voltage-current characteristic of a PEM fuel cell [27]

This parameter is usually set to 2 since higher values do not bring to major improvements [27].

$$\dot{G}_{air} = \frac{W_{disch}}{V_c} \cdot \lambda_{air} \cdot \frac{1}{4 \cdot F} \cdot \frac{\overline{M_{air}}}{y_{O2}} \quad [\frac{kg}{s}] \qquad (16)$$

In eq. (16) the molar fraction of O_2 in the air mixture is considered by the parameter y_{O2} (equal to 21%) and the molar mass of air is approximated to 29 g/mol.

Algorithm

The following algorithm has been implemented into Excel to calculate the performance of the system in each factory:

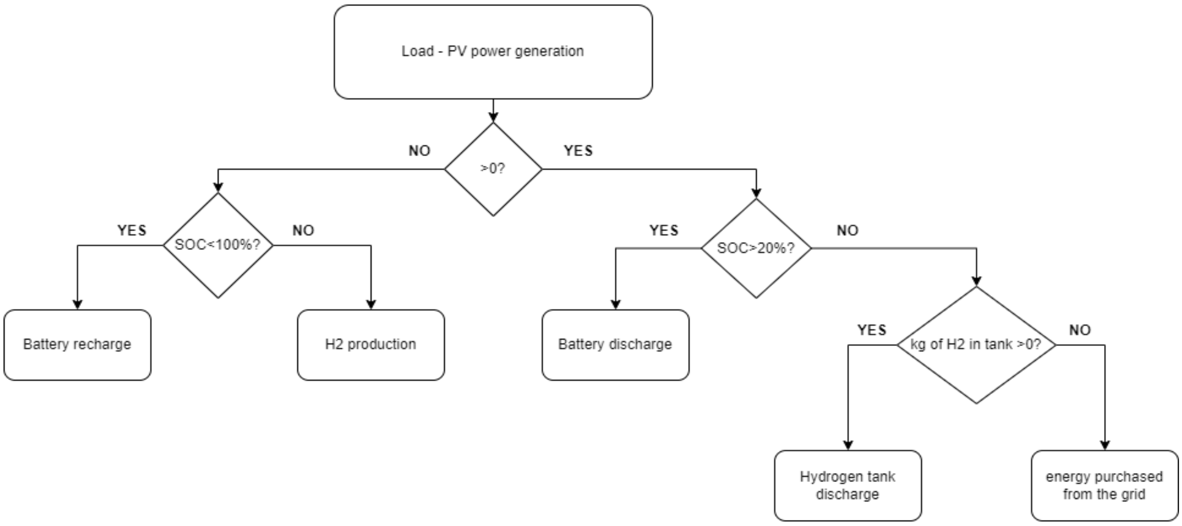

Figure 30 - flowchart of the implemented algorithm

It is important to specify that if the battery SOC is 100% and the energy excess overcomes the electrolyser nominal capacity, the remaining energy is sold.

Factory load by location

In 2020 each considered factory consumed electricity mainly from two different sources: the biggest amount is purchased from the grid, while a smaller percentage is produced by a Diesel generator. In fact, these generators are switched on in case of blackouts and, as stated by the company, they are frequent. Thus, knowing the electricity purchased and the diesel consumed for each month of the year V_{diesel}, an average monthly electricity consumption has been calculated (figure 31), assuming the efficiency η_{gen} of the diesel generator to be 25% [28] and the diesel lower heating value LHV equal to 10 kWh/litre [29] (eq.17).

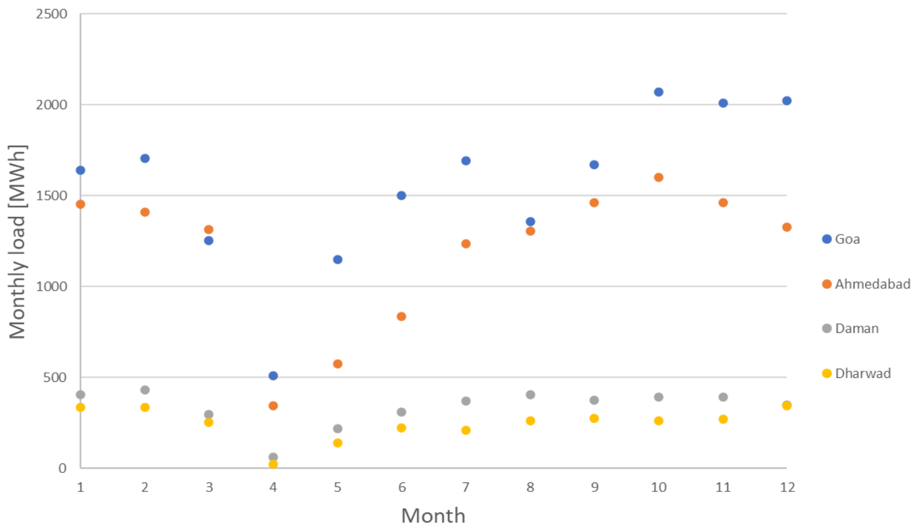

Figure 31 - average monthly load by location

$$E_{generator} = LHV \cdot \eta_{gen} \cdot V_{diesel} [kWh] \quad (17)$$

By dividing each monthly load $E_{monthly}$ for an average number of days $n_{day,av}$ in a month (30 days) and for 24 hours, the average hourly load for each month has been calculated (figure 32). Following this reasoning and as stated by the company, the load is assumed to be constant all over the 24 hours, with no exception between the weekday and the weekend.

$$E_{hourly} = \frac{E_{monthly}}{24 \cdot n_{day,av}} \quad [kWh] \quad (18)$$

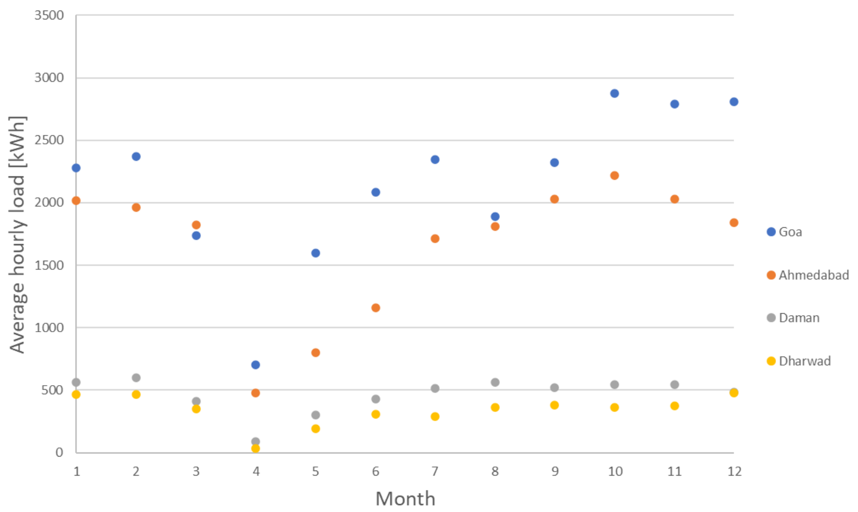

Figure 32 - average hourly load by month by location

What mainly catches the eye in figure 31 and 32 is an abrupt decrease in electricity consumption, above all in April: this can be explained if we think that 2020 has been characterised by COVID-19 pandemic and several countries decided for periods of full lockdown. As IEA reported in figure 33, Indian authorities opted for a full lockdown between the beginning of April and the end of May 2020 (dashed line).

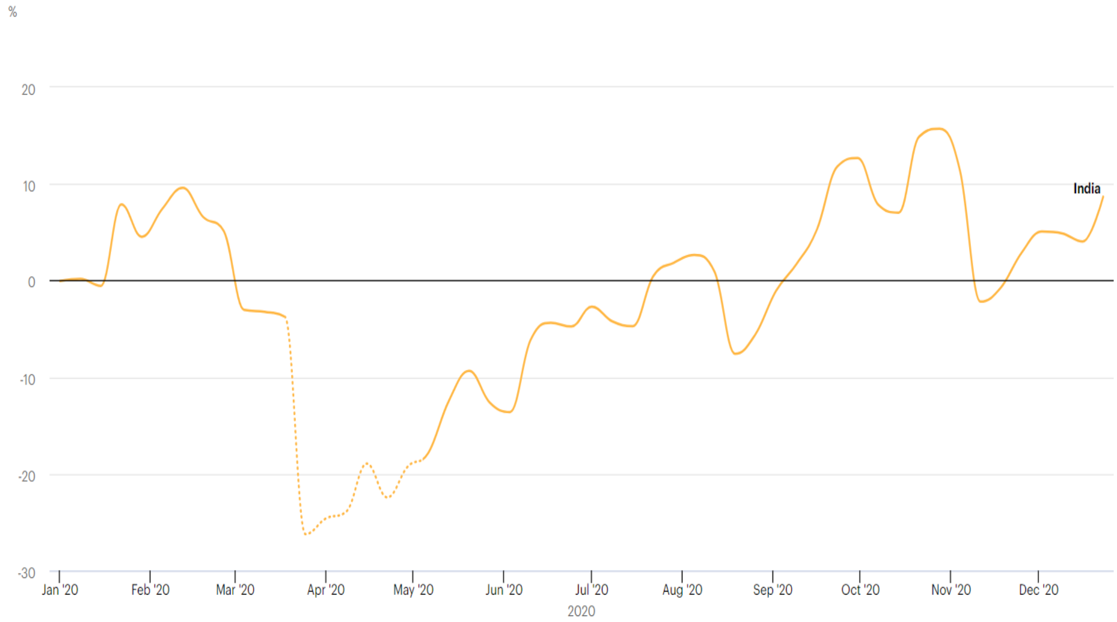

Figure 33 - change in weekly electricity demand in India in 2020 [45]

On average drops up to -25% have influenced the electricity demand in the lockdown period, but as shown in the considered factories, the demand decrease has probably been much more negative, with load reductions in April of up to 90% with respect to March. For this reason, load data have been adjusted in this work in order to obtain a load that is assumed not to be affected by pandemics in the upcoming years. Therefore, the new load has been built considering April and May loads equal to the load in March for each location (figure 34).

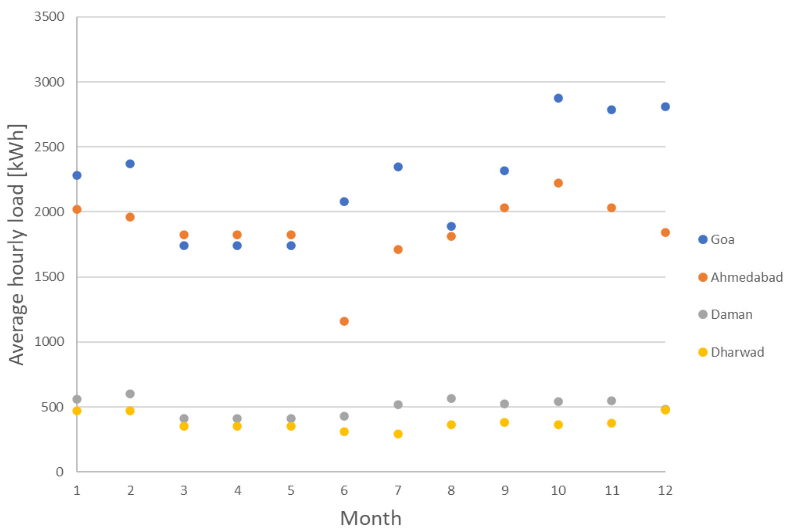

Figure 34 - corrected average hourly load by month by location

Results

Using the technology capacities mentioned before in the Excel algorithm, the following results have been obtained and are divided by location for an easier understanding.

Goa

With 4380 kW of PV installed capacity, the system would be able to cover at least 40% of the total load in the months not affected by Monsoon and by a load higher than 2400 kW (figure 35).

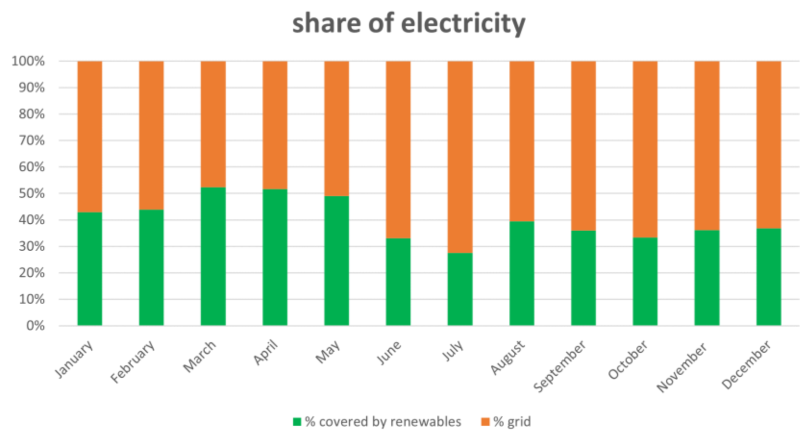

Figure 35 - share of covered load by source in Goa

Focusing of the PEM system, it only works when the energy excess is sufficiently high. In this case it is clear from figure 36 and 37 that the selected PV capacity is not adequate to allow their functioning in periods of low solar irradiance or high loads since a negligible amount of hydrogen is produced and stored.

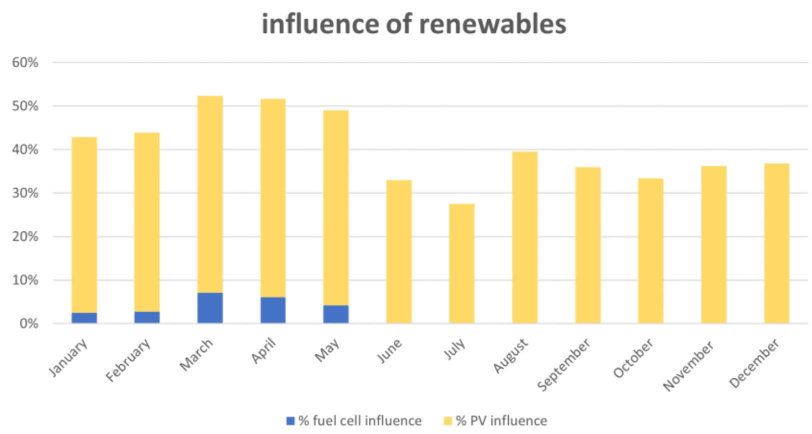

Figure 36 – energy influence of technologies in Goa

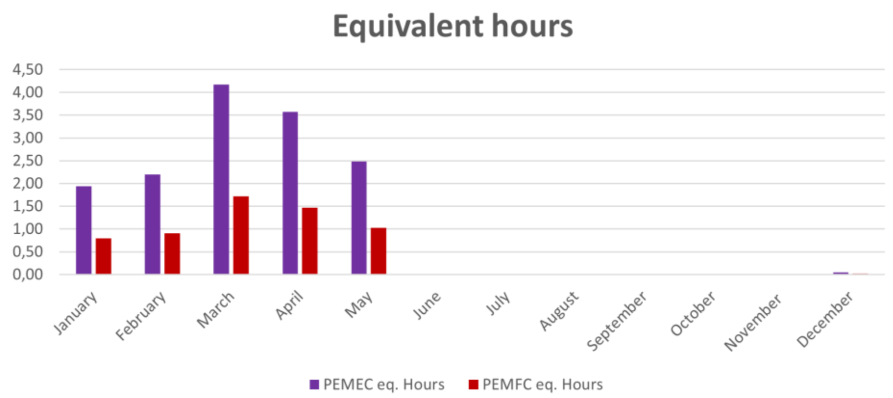

Figure 37 – daily equivalent hours by PEM technology in Goa

Ahmedabad

In this factory the proposed PV capacity is higher than Goa although the lower average load. The results show a higher share of renewables, contributing on average on 50% of the total energy consumed (figure 38).

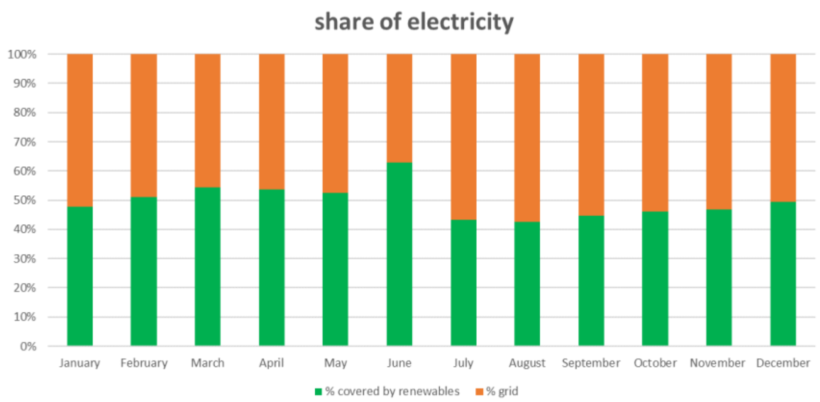

Figure 38 - share of covered load by source in Ahmedabad

PEM technologies have a higher contribution in this case and work for more equivalent hours since there's enough energy to convert to hydrogen and consequently more stored hydrogen to use in case of need (figure 39 and 40).

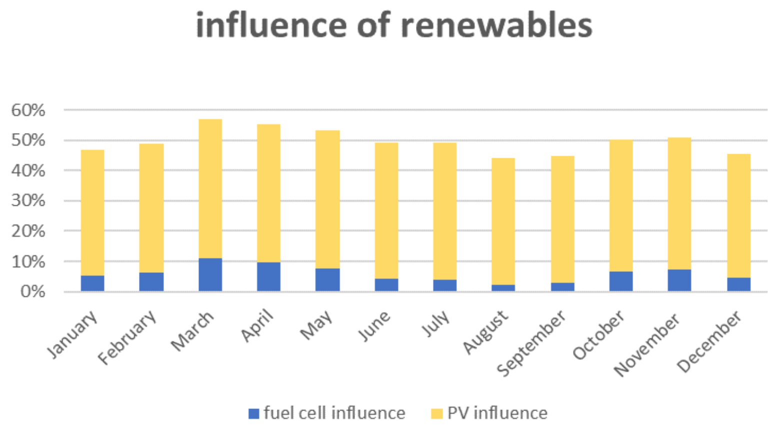

Figure 40 - energy influence on technologies in Ahmedabad

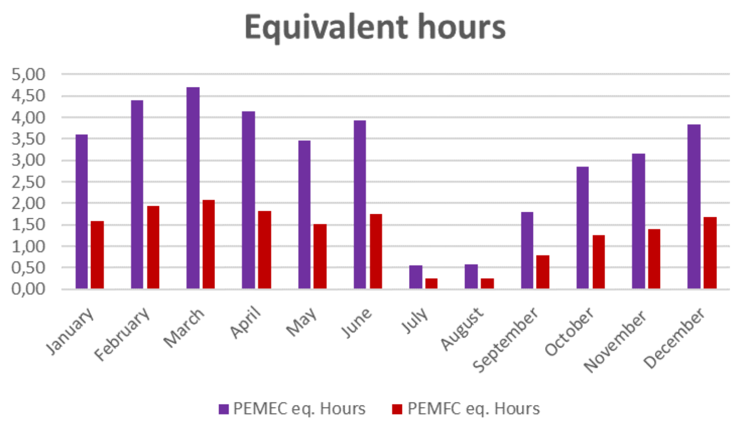

Figure 39 – daily equivalent hours by PEM technology in Ahmedabad

Daman

Daman is characterised by a very low electricity cost (shown in the economic chapter in table 18) and so the software proposed a low PV capacity compared to its load. This is highlighted by watching the

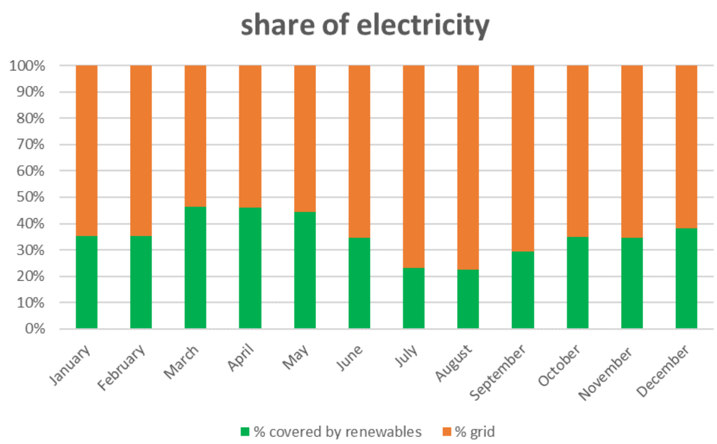

Figure 41 - share of covered load by source in Daman

share of renewable in figure 41, that accounts on average on 35% of the total share and that does not overcome 30% between July and September. The lack of energy excess in 8 months of the year brings to a low exploitation of the PEM system and therefore it would not be convenient to install it from an energy point of view (figure 42 and 43) unless the PV capacity is increased.

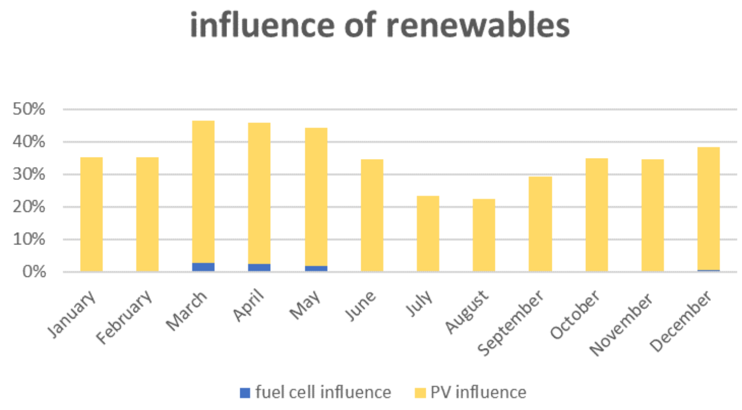

Figure 42 - energy influence on technologies in Daman

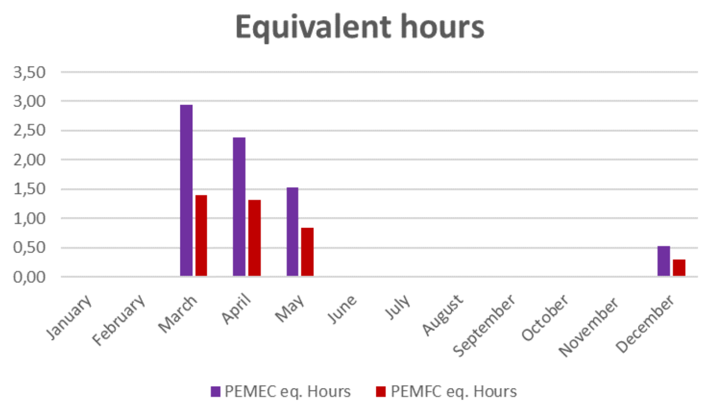

Figure 43 – daily equivalent hours by PEM technology in Daman

Dharwad

In Dharwad Homer Pro suggests 1055 kW of PV and the results are very similar to the Ahmedabad case, since environmental sources are similar, together with the ratio between installed PV capacity and average yearly load. Therefore, the share of renewables accounts for 50% on average (figure 44).

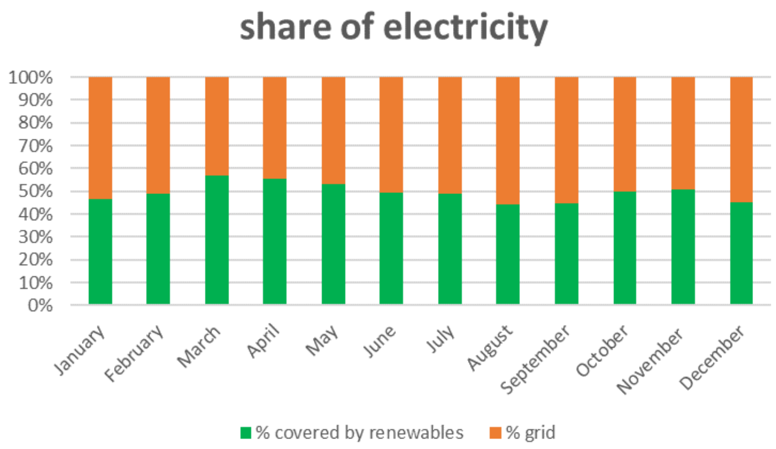

Figure 44 - share of covered load by source in Dharwad

Concerning the PEM system, it gives a non-negligible contribution in the energy share almost every month of the year, except for the Monsoon period (figure 45 and 46).

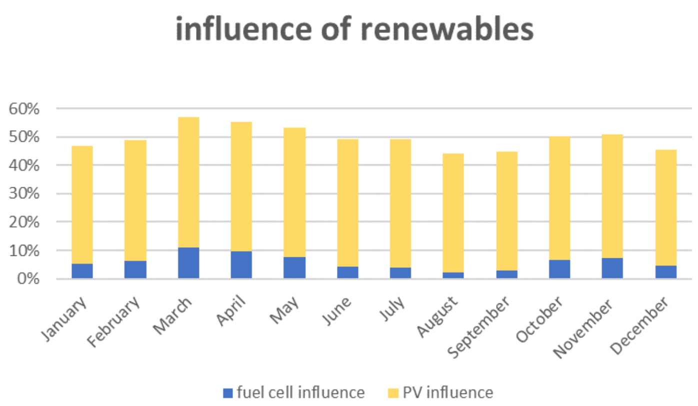

Figure 46 - energy influence on technologies in Dharwad

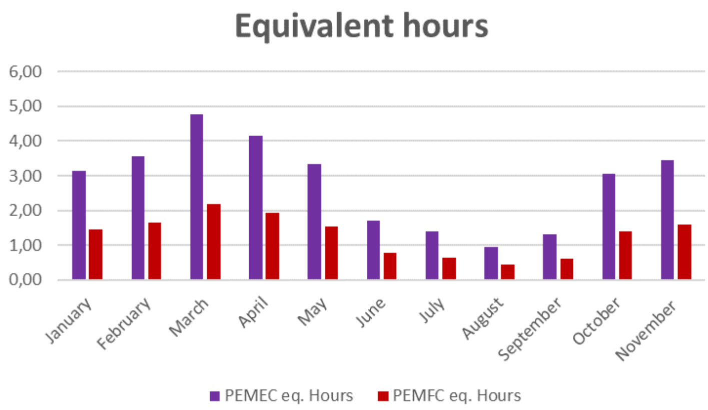

Figure 45 – daily equivalent hours by PEM technology in Dharwad

Emission reduction

The emission calculation has been performed by using an index provided by the company that indicates the kg of equivalent CO2 emission for each kWh of purchased electricity in India. As seen in the first chapter of this work, Indian factories are characterised by important specific emissions, and this is mainly due to unsustainable ways of producing electricity by the Country. Therefore, the emission index is very high, corresponding to 1070 $\frac{g_{CO2,eq}}{kWh_{el}}$ compared to the one of other countries (provided by the company too). Table 12 shows a comparison between the Indian emission factor and the one of five other countries.

Country	*Purchased electricity Emission factor [gCO2,eq/kWh,el]*
India	*1070*
Italy	*550*
United Kingdom	*390*
Spain	*350*
China	*550*
New Zealand	*750*

Table 12 - comparison of emission factors by country

In the previous chapter the load has been modified in order to not consider the influence of the COVID 19 pandemic. Following this reason, the emission base case has been calculated with the corrected load and compared to the possible future implementation of the selected system.

Results are promising since the renewable system implementation brought a strong emission reduction, above all on the factories with a high installed PV capacity over mean load ratio.

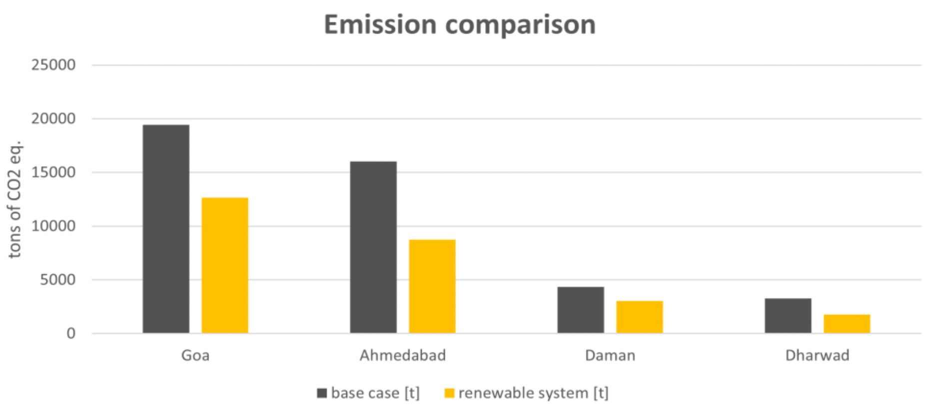

Figure 47 - comparison of the base case emissions and the proposed system ones

Emissions and percentages of this reduction are resumed in the table below.

	Base case [t]	*Renewable system [t]*	*% of emission reduction*
Goa	*19424*	*12651*	*34.9*
Ahmedabad	*16035*	*8751*	*45.4*
Daman	*4327*	*3027*	*30.0*
Dharwad	*3280*	*1782*	*45.7*

Table 13 - reduction of emissions by location

Sensitivities

Starting from the base cases, a sensitivity analysis is performed for each location to see how an increase of the battery and of the installed PV capacity affects the required PEM system capacities and the load coverage. Battery and PV capacities have been increased by 10%, 20% 30% and 40% and results are resumed in the following graphs and table.

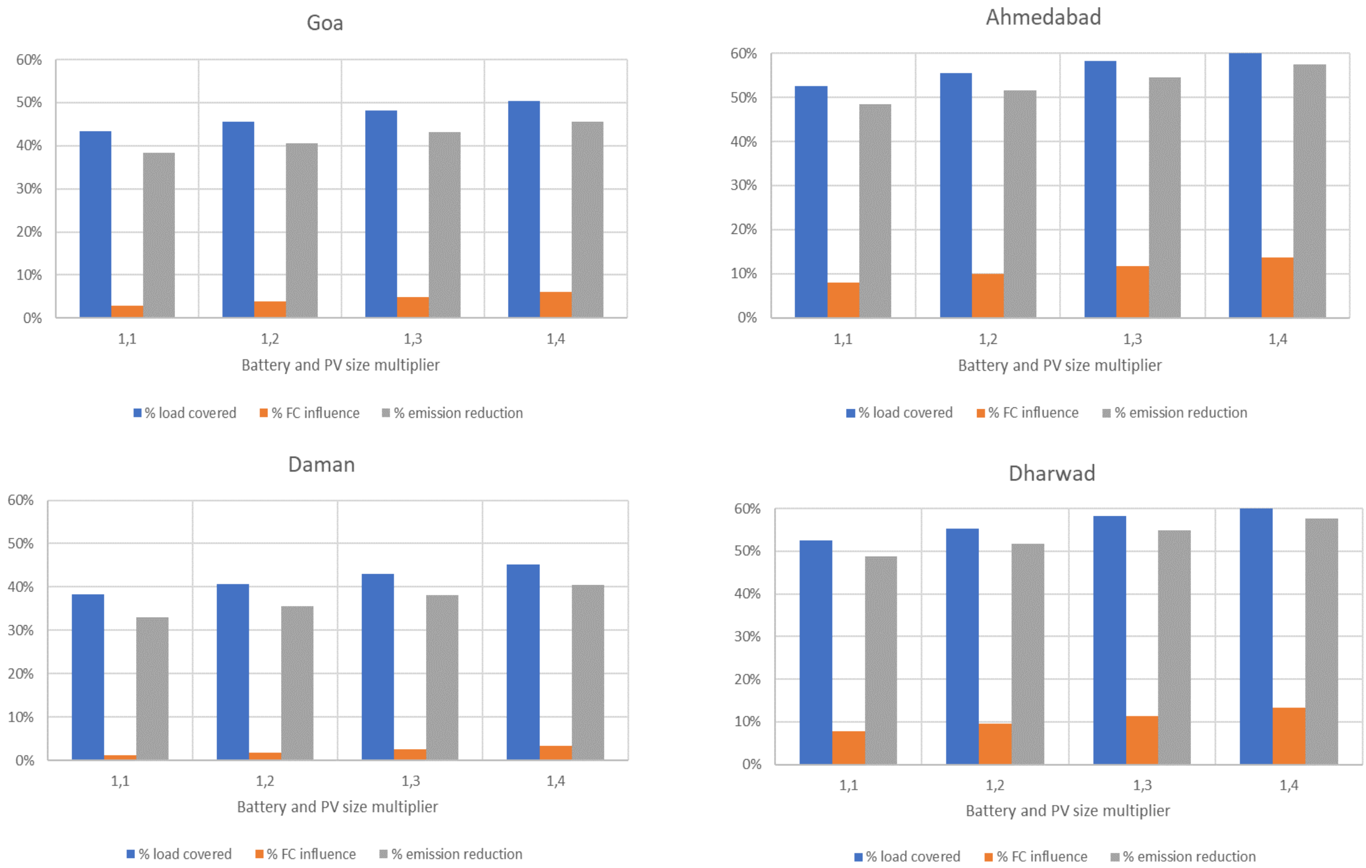

Figure 48 - results on load covered, FC influence and emission reduction by location

Results show that for each 10% increase of the PV and battery installed capacity (with respect to the base case) the percentage of load covered increases between 2.2% and 2.9% according to the PV to mean load ratio (the higher it is, the higher the percentage increase). Also the FC influence is very dependent on the above-mentioned ratio: Goa and Daman are characterised by a relatively low PV to mean load ratio, varying from 1.8 to 2.8 and this influence the fuel cell functioning. Therefore, its influence increases of 1% for each 10% increase of PV plus battery, while for Daman the percentage of increase is lower (0.75% on average).

The story changes when Ahmedabad and Dharwad are considered since their ratio stands between 2.9 and 3.9 and so it permits higher equivalent load hours for the fuel cell and whose influence increases of 1.85% on average for both factories.

On the contrary, emission reduction is less dependent on the PV to load mean ratio and increases of 2.5% for Goa and Daman, while for Ahmedabad and Dharwad it increases of 3% each 10% increase of PV and battery power.

Concerning the PEM system, for every location the fuel cell capacity increases up to a higher limit that is represented by the maximum load of the factory, while the hydrogen storage capacity and the electrolyser power keep rising but with an increasingly lower rate. The size of each technology is resumed in table 14.

Location	Total PV installed [kW]	Battery capacity [kWh]	PEMEC [kW]	H2 storage [kg]	PEMFC [kW]	Compressor [kW]	PV to mean load ratio [-]
Goa							
Base case	4380	2808	2027	169	1740	56	1.95
+10%	4818	3089	2471	227	1740	70	2.14
+20%	5256	3370	2790	260	2370	77	2.34
+30%	5694	3650	3170	304	2370	87	2.53
+40%	6132	3931	3550	350	2370	98	2.73
Ahmedabad							
Base case	4900	2221	2464	235	2221	68	2.64
+10%	5390	2443	2977	290	2019	80	2.90
+20%	5880	2665	3330	342	2221	92	3.17
+30%	6370	2887	3764	395	2221	104	3.43
+40%	6860	3109	4197	453	2221	116	3.70
Daman							
Base case	805	601	291	18	238	9	1.61
+10%	886	661	365	26	413	10	1.77
+20%	966	721	434	35	403	12	1.93
+30%	1047	781	510	43	413	14	2.09
+40%	1127	841	577	52	413	16	2.25
Dharwad							
Base case	1055	479	553	53	470	16	2.78
+10%	1161	527	645	65	470	18	3.06
+20%	1266	575	735	76	479	21	3.34
+30%	1372	623	827	88	479	23	3.61
+40%	1477	671	918	99	479	26	3.89

Table 14 - effect on system characteristics by factory in the sensitivity analysis

Techno-economic analysis

The last part of this work is focused on evaluating the economic feasibility of the integrated systems in the four selected Indian factories. For each system the CAPEX (CAPital EXpenditure) and OPEX (OPerative EXpenditure) have been evaluated and then a cash flow analysis has been done to calculate the Cumulative Cash Flow for each location. Calculations have been performed by taking into account that this system would be installed in 2030 in which a strong price reduction is expected for the considered technologies, especially the PEM ones [30], and a lifetime of 20 years.

CAPEX

In order to estimate the Capex for each technology, mainly four values have been evaluated:

- Cost of the main component of the system, that is the price of PV modules for the PV systems and the price of stacks for fuel cell and electrolyser
- Cost of the Balance Of Plant (BOP), including valves, cables, auxiliary components, controls and sensors, safety and security systems
- Installation cost
- Other indirect capital costs, for example system design, permissions, site preparation, etc...

Photovoltaic system

Currently Indian PV market is characterised by low price of PV modules, ranging between 20 and 40 Indian rupees per Watt (corresponding to 0,26-0,52 $/W) according to IndiaMART, a well-known online marketplace [31]. Obviously, the price may vary widely according to lots of variables, such as the type of manufacturer, the type of PV module, its efficiency and so on.

Concerning the future, the IRENA report "The power to change: solar and wind cost reduction potential to 2025" [32] forecasts a strong cost reduction in the global PV capital expenditure, mainly in the utility-scale: module cost will continue to decline, above all polycrystalline modules thanks to cheaper production processes, installation will require less materials and inverter price will drop thanks to the economies of scale and technological progress. In our analysis the land cost is also taken into account, and, because of no further information, it has been assumed following the base value given in the NETL [33]. Table 15 resumes the expected CAPEX values:

CAPEX categories	*Specific cost*
PV module [$/W$_{DC}$]	*0,21*
BOP [$/W$_{DC}$]	*0,2*
Inverter [$/W$_{DC}$]	*0,091*
Installation [$/W$_{DC}$]	*0,15*
Indirect CAPEX [$/W$_{DC}$]	*0,2*
Total [$/W$_{DC}$]	*0,852*
Land [$/acre]	*3000*

Table 15 – PV input CAPEX costs

Concerning the battery, its CAPEX is chosen basing on a CSIRO report [10] that assumes future optimistic prices for Li-ion batteries in 2030. Those values are resumed in table 16.

Battery CAPEX	*Specific cost*
Li-ion battery cost [$/kWh]	200

Installation cost [%CAPEX]	10

Table 16 - Li-ion Battery input CAPEX costs

PEMFC and PEMEC

As cited in the previous chapters, fuel cells and electrolysers costs are expected to drop thanks to economies of scale and future developments. Nowadays the cost of a large PEM fuel cell (>0.4 MW) ranges between 2000 and 3500 $/kW [7], but on optimistic assumptions IEA forecasts its reduction to 425 $/kW by 2030 [9]. This more optimistic value has been used as input in this work. Since no further data for the installation and the indirect costs of PEM fuel cells have been found, they have been assumed to be equal to those expected in an undefined future for PEM electrolyser, described in [30]. Table 17 resumes the fuel cell specific costs used as input:

CAPEX categories	*Specific cost*
FC Cell stack + BOP [$/kW]	*425*
Installation (multiplier of stack + BOP) [-]	*1.1*
Indirect CAPEX – Site preparation [% of stack + BOP]	*18.85*
Indirect CAPEX – project contingency [% of stack + BOP]	*15*
Indirect CAPEX – Engineering and design [$/kW]	*14.65*
Indirect CAPEX – Permitting costs [$/kW]	*8.79*

Table 17 - PEM fuel cell input CAPEX costs

Concerning PEM electrolysers, the current average cost is about 2000 $/kW and has been evaluated comparing different papers in a recent report on the cost of Power-to-gas technologies for the STORE & GO project [8]. For the future IEA assumes a specific cost of 1500 $/kW (that includes stack and BOP) by 2030 without specifying the unit size [9]. Differently, a NREL document [30] proposes a much lower CAPEX cost of 450 $/kW for an undefined future, specifying that 38% of the cost is related to the stack and the remaining is related to the BOP. For this work, again an optimistic future is considered and the NREL proposed value is assumed, together with the indirect costs. Values of PEMEC are depicted in the table below:

CAPEX categories	*Specific cost*
Electrolyser Cell stack + BOP [$/kW]	*450*
Installation (multiplier of stack + BOP) [-]	*1.1*
Indirect CAPEX – Site preparation [% of stack + BOP]	*18.85*
Indirect CAPEX – project contingency [% of stack + BOP]	*15*
Indirect CAPEX – Engineering and design [$/kW]	*14.65*
Indirect CAPEX – Permitting costs [$/kW]	*8.79*

Table 18 - PEM electrolyser input CAPEX costs

In this work the hydrogen compressor cost is assumed to be included in the BOP of the PEMEC.

The hydrogen storage cost is assumed to be 450 $/kg in the future according to a technical report of the National Renewable Energy Laboratory (NREL) [34], while its maintenance is considered negligible in this work.

OPEX

Differently from CAPEX, the OPEX is related to operation and maintenance (O&M) costs of the systems, it must be accounted every year in the cash flow analysis, and it can be mainly of two types: fixed and variable. In this work only fixed O&M have been considered.

Photovoltaic systems

For PV systems the main OPEX costs are related to the module cleaning and the module integrity check, together with a global check of the BOP. Therefore, fixed operational costs have been considered equal to 1 Indian rupee for each installed Watt, corresponding to 0,013 $/W, as resumed in table 19, together with the battery cost [35].

System	*Yearly OPEX*
PV [$/W]	*0.013*
Li-ion Battery[%CAPEX/year]	*2.02*

Table 19 - OPEX for PV systems

PEMFC and PEMEC

The Operative Expenditure of the two PEM technologies has been evaluated from different sources and always assuming an optimistic future. A 2020 U.S. report [36] evaluated the actual OPEX of a system of PEMFC and PEMEC, both with nominal size equal to 100 MW, to be 12.8 $/kW/year. For lower nominal power (in the case of this work) and future perspectives, Cigolotti et al. [7] forecast a yearly cost for a PEMFC with power higher than 400 kW to be 2.26 c$/kWh/year, so depending on the output energy. Concerning the electrolyser, the proposed value of NREL report [30] is taken as assumption and calculated as a percentage of the CAPEX, together with the cost of stack replacement.

A recent report of the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) [37] expects a future stack replacement of a PEMFC prime mover of 1 MW to be every 5 years approximately. Since in our case the fuel cell is used as back-up system and considering a much lower number of working hours, the stack replacement is assumed to occur every 10 years. Also in this case, without any further information, the cost of stack replacement for PEMFC is assumed to be calculated in the same way as PEMEC. Table 20 and 21 summarise the assumed data:

O&M category	*Value*
Yearly costs [c$/kWh/year]	*2.26*
Durability [hours]	*60000*
Stack Replacement	*After 10 years*
Cost of stack replacement [% of CAPEX]	*12%*

Table 20 - OPEX for PEMFC system

O&M category	*Value*
Yearly costs [% of CAPEX/year]	*2.8*
Durability [hours]	*60000*
Stack Replacement	*After 10 years*
Cost of stack replacement [% of CAPEX]	*12%*

Table 21 - OPEX for PEMEC system

Cash flow analysis

The cash flow analysis is an important method that permits to know whether the considered system will lead to earning or losing money, knowing the movement of money in and out of the chosen business. Depreciation is the first thing to be considered in the cash flow analysis: it consists in a fiscal benefit that allows to recover part of the investment in the first years of the plant through the application of fiscal detraction on part of the investment cost. It is expressed as:

$$Dep.Rate = \frac{TPC\ [\$]}{Dep.Time\ [y]} \quad (19)$$

Where:

- TPC is the total investment cost, expressed in $
- Dep. Time is the depreciation time, expressed in years

In this work the depreciation time is assumed to be 10 years as standard value for each implemented technology. The second important parameter to be calculated is the revenue: in our case the source of incomes is given by the savings of electricity, that is self-produced for a good fraction of the day. It is calculated in the following way (eq.20).

$$Annual\ revenue = C_{el,purch} \cdot \sum_{i=1}^{12}(total\ energy\ required_i - energy\ purchased_i) \quad [\$] \quad (20)$$

To evaluate the cost of purchased electricity the actual values of industrial electricity prices in India in 2019 were taken from the Indian report on power utilities [38]. It changes according to the Indian federal state and so on the location of each factory and it is assumed to increase by 2% every year. The initial base value for this analysis will therefore consider the price of electricity starting from 2030 and increasing every year according to the above-mentioned assumption. Table 22 resumes the electricity cost by location.

	2019 price [$/kWh]	*2030 assumed starting price [$/kWh]*
Goa	*0.075*	*0.094*
Ahmedabad	*0.100*	*0.124*
Daman	*0.061*	*0.075*
Dharwad	*0.110*	*0.136*

Table 22 - cost of purchased electricity and future assumption

Unfortunately, up to now no subsidy for industry in installing PV power is present [39] so it is not considered in this economic analysis.

Now the yearly cash flow can be evaluated by subtracting the costs to the incomes of the selected year. Year 0 is usually chosen as the starting year, where only investment costs are present. From the following year revenues and OPEX costs are considered. Another important parameter is the taxation, that is imposed only when the cash flow is positive. The taxation rate t depends on the amount of revenues and increases with their increase up to a limit value. Table 23 shows the range of incomes and its Indian tax share, converted in dollars for simpler understanding:

Income Tax Slab	*Tax rates*
0 $ - 3250 $	*Nil*
3251 $ - 6500 $	*5%*

6501 $ - 9750 $	*163 $ + 10% of total income exceeding 6501 $*
9751 $ - 13000 $	*488 $ + 15% of total income exceeding 9751 $*
13001 $ - 16250 $	*975 $ + 20% of total income exceeding 13001 $*
16251 $ - 19500 $	*1625 $ + 25% of total income exceeding 16251 $*
Above 19501 $	*2438 $ + 30% of total income exceeding 19501 $*

Table 23 - Indian tax rate per income tax slab [40]

Finally, the cash flow can be written as:

$$Cash\ flow\ \left[{}^{\$}/_{y}\right] = Incomes - Costs - Taxes$$
$$= Incomes - Costs - t \cdot (Incomes - Costs - Dep.Rate) \quad (21)$$

for a number of years equal to the depreciation time and then:

$$Cash\ flow\ \left[{}^{\$}/_{y}\right] = Incomes - Costs - Taxes$$
$$= Incomes - Costs - t \cdot (Incomes - Costs) \quad (22)$$

up to the lifetime of the plant.

Since the value of money changes in time, it must be considered in future cash flows (n-th year with respect to the initial year n_0) through a parameter: the discounting factor.

$$Discounting\ factor = (1 + WAAC)^{-(n-n_0)} \quad (23)$$

WAAC is the Weight Average Cost of Capital, and it is used to take into account the percentage of investment covered by equity $\%_e$ (owner capital) and by debt $\%_d$, their respective costs C_e and C_d, and the taxation rate t, and it is expressed as follow:

$$WACC = \%_e \cdot C_e + \%_d \cdot C_d \cdot (1 - t) \quad (24)$$

Costs and percentages of the WACC can be estimated by the NETL report [33] according to the plant financial structure. In particular, the financial structure depends on two main factors: the type of investor and the level of risk of the investment. Investor can be IOU (Investor-Owned Utility) or IPP (Independent Power Producer) and the related investment can have low or high risk, depending on how mature the technology is at the moment.

In this work the selected company has been considered as an IPP and the introduced technologies to be mature in the market and so a low-risk investment. Table 24 resumes the considered values:

	% Of total	*Current Nominal Dollar Cost*	*Weighted Current Nominal Costs*	*After Tax Weighted Cost of Capital*
Debt	*70%*	*6.5%*	*4.55%*	
Equity	*30%*	*20%*	*6%*	
Total			*10.55%*	*9.185%*

Table 24 - Financial structure for IPP at low risk

The present cash flow is then determined as:

$$Present\ cash\ flow\ \left[{}^{\$}/_{y}\right] = Cash\ flow \cdot Discounting\ factor \quad (25)$$

In the end, by summing up the various present cash flows each year, the cumulative cash flow can be evaluated:

$$Cumulative\ cash\ flow\ _i = \sum_{n=0}^{i} Present\ cash\ flow_n \quad (26)$$

When the cumulative cash flow becomes positive, it means that the plant has fully covered the investment and from that moment on it starts to earn money.

Results

The Net Present Value has been calculated for the base case for each factory and is resumed in the graphs below.

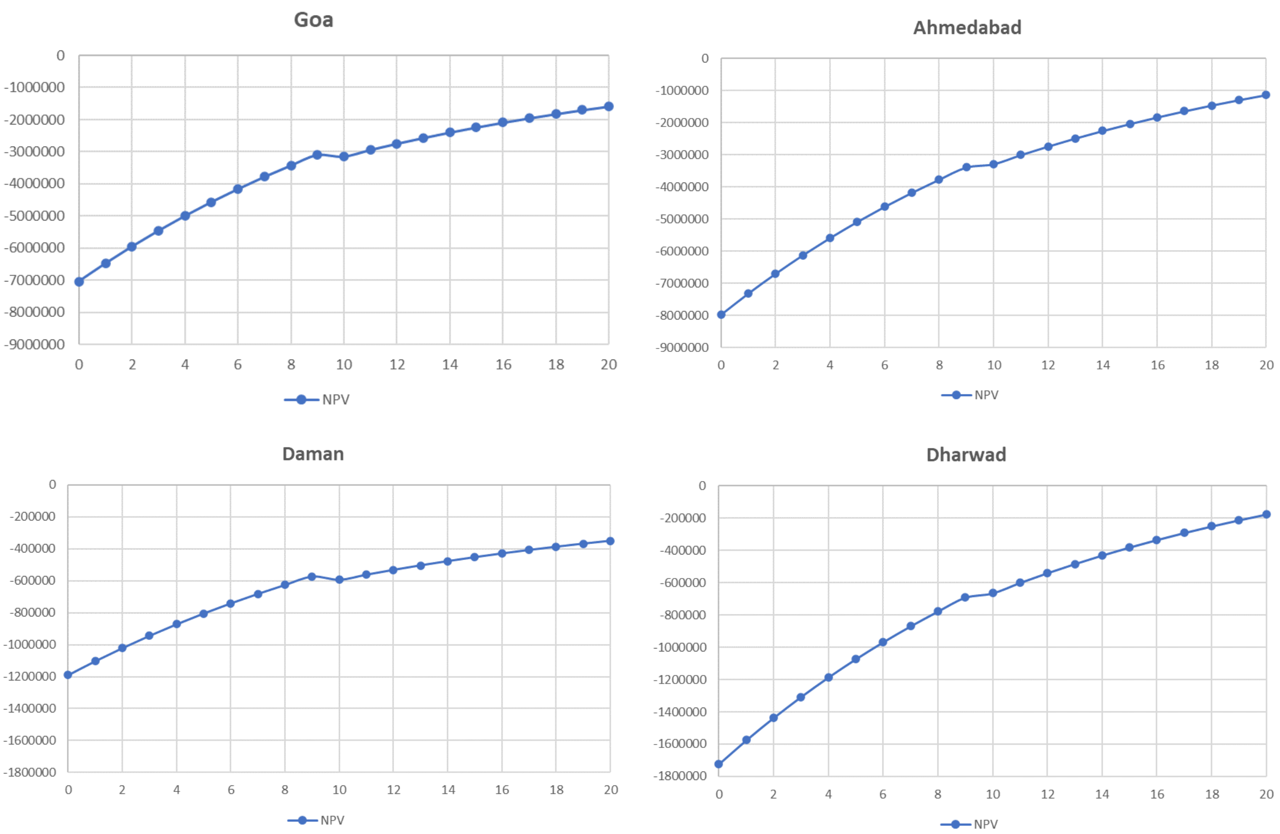

Figure 49 - NPV for the base case for each factory

With all the assumptions made in the previous chapters, the results show a negative NPV for all the considered factories. The main cause that brings to a negative cumulative cash flow is the cost of purchased electricity, that is still low compared to industrial electricity prices collected in an Excel document by the UK Department for Business, Energy & Industrial Strategy basing on Eurostat and IEA data [41]. It shows an IEA median value of 0.105 $/kWh and for the EU 15 countries this value increases to 0.122 $/kWh. Comparing them to the 2019 Indian value, there is an important difference, above all on Goa and Daman electricity prices since they are less than half IEA median value.

Another cause is the fact that the PEM system actually works as back-up only a few hours a day and mainly in the months with higher radiation and so this is not enough to recover its large investment cost.

A sensitivity analysis will then be performed on the electricity price increasing trend and on the PEM technology costs to detect suitable values to reach a positive NPV.

Sensitivity analysis

This analysis has been performed by combining the rate of electricity price and the cost of the total PEM technologies. The annual increasing electricity price trend is varied between 2% and 5% with a step of 0,25%, while PEM prices are varied from the base case values to 25% lower cost, with a decreasing step of 5%. Results are divided by factory.

Selected electricity price trends are not so unrealistic if we compare 2019 industrial electricity prices of the selected locations with 2011 values: in fact, basing on the comparison between annual reports of the Power Finance Corporation Ltd. [42], they increased up to 91% with respect to 2011. The following graph and table show the above-mentioned price evolution. Please notice that the least recent value for Daman available on the reports was of 2018.

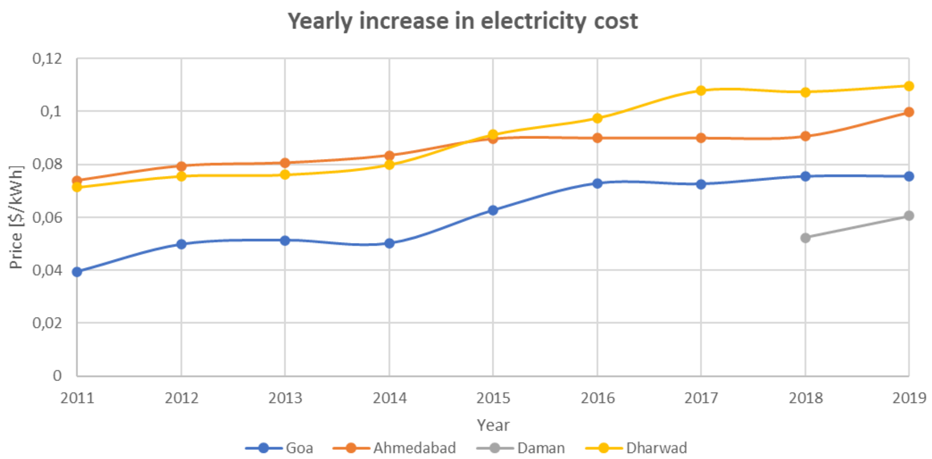

Figure 50 - Electricity price evolution in 2011-2019 for the selected locations

Location	*2011 el. Price [$/kWh]*	*2018 el. Price [$/kWh]*	*2019 el. Price [$/kWh]*	*% of increase (2019 w.r.t. least recent year)*
Goa	*0.0395*	*0.0754*	*0.0754*	*90.8%*
Ahmedabad	*0.0738*	*0.0906*	*0.0997*	*35%*
Daman	*-*	*0.0524*	*0.0606*	*15.6%*
Dharwad	*0.0715*	*0.1074*	*0.1097*	*53.6%*

Table 25 - 2011-2019 electricity prices and % of increase

Goa

	NPV Goa	PEM CAPEX reduction					
	-1586498	0%	5%	10%	15%	20%	25%
annual increasing trend	2,00%	-1586498	-1456690	-1326882	-1197074	-1067267	-937459
	2,25%	-1291147	-1161340	-1031532	-901724	-771916	-642108
	2,50%	-993227	-863419	-733611	-603804	-473996	-344188
	2,75%	-689494	-559686	-429878	-300071	-170263	-40455
	3,00%	-378760	-248952	-119144	10663	140471	270279
	3,25%	-59644	70164	199972	329780	459587	589395
	3,50%	274967	404775	534583	664390	794198	924006
	3,75%	626427	756234	886042	1015850	1145658	1275465
	4,00%	995607	1125415	1255223	1385030	1514838	1644646
	4,25%	1383427	1513235	1643043	1772851	1902658	2032466
	4,50%	1790854	1920662	2050469	2180277	2310085	2439893
	4,75%	2218905	2348713	2478520	2608328	2738136	2867944
	5,00%	2668652	2798460	2928267	3058075	3187883	3317691

Figure 51 – Goa NPV sensitivity results

In order to obtain a positive NPV in Goa, an electricity increasing trend of at least 3.5% is required with the base PEM price. In case of a stronger PEM cost reduction with respect to the expected future prices, a positive cash flow can be obtained with a lower electricity trend.

	Payback	PEM CAPEX reduction					
	no	0%	5%	10%	15%	20%	25%
annual increasing trend	2,00%	no	no	no	no	no	no
	2,25%	no	no	no	no	no	no
	2,50%	no	no	no	no	no	no
	2,75%	no	no	no	no	no	no
	3,00%	no	no	no	no	no	19
	3,25%	no	no	19	19	18	17
	3,50%	19	18	18	17	17	16
	3,75%	18	17	16	16	15	15
	4,00%	16	16	15	15	14	14
	4,25%	15	15	14	14	14	13
	4,50%	14	14	13	13	13	12
	4,75%	13	13	13	12	12	12
	5,00%	13	12	12	12	11	11

Figure 52 - Goa payback time sensitivity results

As expected, the payback time remains high also in the more optimistic case and is equal to approximately 11 years for the best case. A high electricity price increase or a strong CAPEX reduction bring to a payback time that does not overcome 13 years.

Ahmedabad

	NPV Ahmedabad	PEM CAPEX reduction					
	-1131550	0%	5%	10%	15%	20%	25%
annual increasing trend	2,00%	-1131550	-969655	-807760	-645866	-483971	-322076
	2,25%	-773854	-611960	-450065	-288170	-126275	35620
	2,50%	-398272	-236378	-74483	87412	249307	411202
	2,75%	-3883	158011	319906	481801	643696	805591
	3,00%	410283	572177	734072	895967	1057862	1219757
	3,25%	845246	1007141	1169036	1330931	1492825	1654720
	3,50%	1302082	1463976	1625871	1787766	1949661	2111556
	3,75%	1781921	1943815	2105710	2267605	2429500	2591395
	4,00%	2233219	2395114	2557009	2718904	2880799	3042693
	4,25%	2751171	2913066	3074960	3236855	3398750	3560645
	4,50%	3295324	3457219	3619113	3781008	3942903	4104798
	4,75%	3867042	4028937	4190832	4352726	4514621	4676516
	5,00%	4467761	4629656	4791551	4953445	5115340	5277235

Figure 53 - Ahmedabad NPV sensitivity results

Starting from a higher electricity price, Ahmedabad shows more positive results, with a positive NPV for the base case reached with 3% increasing trend in electricity price. For higher trends (higher than 3.25%) the base case already brings to good net revenues compared to the initial investment cost (17% of net revenues from the investment). This percentage also increases in case of a lowering of the PEM CAPEX.

	Payback	PEM CAPEX reduction					
	no	0%	5%	10%	15%	20%	25%
annual increasing trend	2,00%	no	no	no	no	no	no
	2,25%	no	no	no	no	no	no
	2,50%	no	no	no	no	19	18
	2,75%	no	no	19	18	17	17
	3,00%	19	18	17	17	16	16
	3,25%	17	17	16	15	15	14
	3,50%	16	15	15	14	14	14
	3,75%	15	14	14	14	13	13
	4,00%	14	14	13	13	12	12
	4,25%	13	13	12	12	12	11
	4,50%	12	12	12	11	11	11
	4,75%	12	12	11	11	11	10
	5,00%	11	11	11	10	10	10

Figure 54 - Ahmedabad payback time sensitivity results

Compared to Goa, the payback time results are slightly better since an improvement of one of the two variables lowers the time by two years and the more optimistic scenario by one year.

Daman

	NPV Daman	PEM CAPEX reduction					
	-350349	0%	5%	10%	15%	20%	25%
annual increasing trend	2,00%	-350349	-332237	-314126	-296014	-277902	-259791
	2,25%	-300627	-282515	-264403	-246292	-228180	-210069
	2,50%	-250478	-232366	-214254	-196143	-178031	-159920
	2,75%	-199695	-181584	-163472	-145361	-127249	-109137
	3,00%	-147956	-129844	-111733	-93621	-75510	-57398
	3,25%	-94977	-76866	-58754	-40642	-22531	-4419
	3,50%	-40545	-22433	-4322	13790	31901	50013
	3,75%	15616	33728	51839	69951	88063	106174
	4,00%	74130	92242	110353	128465	146577	164688
	4,25%	135598	153710	171821	189933	208045	226156
	4,50%	200174	218285	236397	254509	272620	290732
	4,75%	268018	286130	304242	322353	340465	358576
	5,00%	339302	357413	375525	393637	411748	429860

Figure 55 - Daman NPV sensitivity results

Since Daman is the location with the lower electricity cost between the four, a positive NPV will be possible if at least an annual energy increase of 3.75% occurs for the base case. For the same reason, together with a low PEM system exploitation, the CAPEX reduction influences less the Net Present Value compared to the other factories.

	Payback	PEM CAPEX reduction					
	no	0%	5%	10%	15%	20%	25%
annual increasing trend	2,00%	no	no	no	no	no	no
	2,25%	no	no	no	no	no	no
	2,50%	no	no	no	no	no	no
	2,75%	no	no	no	no	no	no
	3,00%	no	no	no	no	no	no
	3,25%	no	no	no	no	no	no
	3,50%	no	no	no	no	19	19
	3,75%	no	19	19	18	18	17
	4,00%	18	18	17	17	17	16
	4,25%	17	17	16	16	15	15
	4,50%	16	16	15	15	14	14
	4,75%	15	15	14	14	14	13
	5,00%	14	14	13	13	13	13

Figure 56 - Daman payback time sensitivity results

In this case Daman is characterised by the highest payback time: for the optimal case it is not lower than 13 years, while it increases to 14-15 years for either a strong annual electricity price increase or a PEM CAPEX reduction.

Dharwad

	NPV Dharwad	PEM CAPEX reduction					
	-176979	0%	5%	10%	15%	20%	25%
annual increasing trend	2,00%	-176979	-141562	-106146	-70730	-35313	103
	2,25%	-96108	-60692	-25276	10140	45557	80973
	2,50%	-11194	24222	59638	95054	130471	165887
	2,75%	77972	113388	148804	184220	219637	255053
	3,00%	171609	207025	242441	277858	313274	348690
	3,25%	269948	305364	340781	376197	411613	447030
	3,50%	373232	408649	444065	479481	514898	550314
	3,75%	470563	505979	541395	576811	612228	647644
	4,00%	582033	617450	652866	688282	723698	759115
	4,25%	699135	734551	769968	805384	840800	876216
	4,50%	822161	857577	892993	928409	963826	999242
	4,75%	951418	986835	1022251	1057667	1093083	1128500
	5,00%	1087233	1122649	1158065	1193482	1228898	1264314

Figure 57 - Dharwad NPV sensitivity results

Dharwad is the location with the highest initial purchased electricity price and for this reason a higher increasing energy price trend leads to very high positive Net Present Values. For no PEM Capital Expenditure reduction, net revenues are reached already with a 2.75% energy increasing trend., while this value lowers to 2.5% just by decreasing the PEM CAPEX by 5%.

	Payback	PEM CAPEX reduction					
	no	0%	5%	10%	15%	20%	25%
annual increasing trend	2,00%	no	no	no	no	no	no
	2,25%	no	no	no	no	19	18
	2,50%	no	no	19	18	18	17
	2,75%	19	18	17	17	16	16
	3,00%	17	17	16	16	15	14
	3,25%	16	15	15	14	14	13
	3,50%	15	14	14	13	13	13
	3,75%	14	14	13	13	12	12
	4,00%	13	13	12	12	12	11
	4,25%	12	12	12	11	11	11
	4,50%	12	11	11	11	11	10
	4,75%	11	11	11	10	10	9
	5,00%	11	10	10	10	9	9

Figure 58 - Dharwad payback time sensitivity results

The related payback time is encouraging, corresponding to 9 years for the optimal case and between 11 and 12 years for an optimistic combination of the two variables.

Conclusions

This work aims at performing a feasibility study to decrease the emissions of four plastic closure Indian factories by proposing a suitable renewable system that combines the mature concept of photovoltaic modules (together with a Li-ion battery covering 1 hour in max load conditions) with a Proton-Exchange Membrane electrolyser and fuel cell. Starting from the required load for each factory and considering it constant for each month, the Homer Pro software gave an initial optimal value of the PV size in case of only its presence in the system. PV optimal size is influenced by the cost of electricity, that is lower in Goa and Daman with respect to Ahmedabad and Dharwad. Therefore, it characterizes the whole analysis since a lower installed PV size brings to a lower energy excess to exploit. Then, the energy excess is calculated to dimension respectively the electrolyser, the hydrogen tank (according to the maximum amount of hydrogen produced) and the fuel cell.

Results show that the selected technology sizes can greatly reduce the factory emissions by 35% up to 46% according to the location. The share of load covered by renewable, instead, depends a lot on the month since between June and August Indian weather is characterised by Monsoon that brings rains and therefore to a lower solar radiation. Nevertheless, on average the annual load covered varies between 35% and 50%. Each 10% increase of the installed PV power and of the battery capacity improves the above-mentioned percentages on average by 2.5% on the covered load and of 2.75% on the emission reduction.

From an economic point of view the base case of each factory does not permit any positive NPV: this is mainly due to the low cost of electricity in India with respect for example to different European countries and to the fact that in this case the PEM system equivalent hours are too low to bring enough revenues to cover their initial investment. The sensitivity analysis studies how the combination of PEM capital expenditure reduction and electricity price increase could make the base case investment economically feasible and show that, except for Daman, a slight reduction in PEM prices (5%-10% less) and an annual energy increasing trend between 2.75% and 3.25% could make the investment economically feasible. The payback time would still remain quite high unless optimistic improvements occur both in the technology cost reduction and in the electricity price.

In India further government subsidies on PV and PEM technologies for industries are not present at the moment and therefore not considered in this work, but their future possible introduction could make these types of investment more feasible.

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