Supplementary Material: Climate-energy-water nexus in Brazilian oil refineries

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1. CAESAR - Carbon and Energy Strategy Analysis for Refineries

The CAESAR – Carbon and Energy Strategy Analysis for Refineries, used by this study, is a simulation tool performed within Excel (Visual Basic Model), and relies on refining schemes, including the following units´ energy and mass balances: atmospheric distillation, vacuum distillation, alkylation, atmospheric residue delayed coking, vacuum residue delayed coking, propane desasphalter, catalytic reformer, fluid catalytic cracker, hydrocracker, residue fluid catalytic cracker, hydrotreaters (naphtha, diesel, kerosene and instable products), hydrotreatment of finished gasoline, lube unit, and hydrogen generation unit. The processing units' capacities are determined, as well as the processed feedstocks, specific utilities consumption (steam, fuel and hydrogen) and specific water consumption. The outputs of the tool consist of the final energy consumption, CO_2 emissions, oil products output, and refineries´ water consumption and demand.

The model consists of 12 sheets named: Menu, Input, Scenario, Production, Alerts, Simulation P01, P02, P03, P04 and P05, Measures, Mitigation and Mitigation Graphs. The first sheet of the simulator is called "Menu". It has the name of the simulator, as well as the menu itself, with the hyperlinks of the respective flaps that constitute the simulator. In the "Input" sheet, the following data should be inserted: total capacities of the refinery´s processing units (including or not greenfield units and/or units´ revamps); atmospheric distillation campaign[1] (naphtha, diesel or kerosene campaigns); and type of HGU module (based on naphtha or natural gas fed steam reform). The modification of the input data allows redesign the entire simulation. The

[1] Campaign, in this case, means maximizing the production of a given cut (naphtha, kerosene and distillates) in the atmospheric distillation unit, through typical yields for different crude oils. These campaigns can be modified at any time, what leads to a new derivative production profile.

tool is prepared (mass and energy balances) for six types of crudes[2] (**Table 1**), whose blend should be defined by the user. The yields of the atmospheric distillation unit for each type of oil is presented in **Table 2**.

Table 1 - Types of crude oils available in CAESAR

Category	Type	° API	Sulphur (ppm)
Crude Oil 1	Arabian Light	33.4	1.80%
Crude Oil 2	Bonny Light	37.6	0.13%
Crude Oil 3	Light[6]	40.1	0.18%
Crude Oil 4	Medium TR[7]	28.4	0.61%
Crude Oil 5	Heavy[8]	20.3	0.74%
Crude Oil 6	Medium[9]	29.3	0.36%

[6]Represented by the African oil Brass River with a 40.1°API, sulfur content 0.18% in mass term and similar yields to the Brazilian oil Piranema (ANP, 2013); [7]The type Medium TR (total reserves) is represented by the Brazilian oil Barracuda with a 24.8°API, and Sulphur content of 0.61% in mass term (BARROS and SZKLO, 2015); [8]Represented by the Brazilian oil Marlim with a 20.3°API and a Sulphur content of 0.74% in mass term (BARROS and SZKLO, 2015); [9]The Medium type is represented by the Brazilian Oil Lula with a 29.3°API and a Sulphur content of 0.36% in mass term.

Source: BERGERSON et al. (2017); BARROS and SZKLO (2015)

The "Scenarios" sheet includes: the growth rate of supply and demand of natural gas and refinery fuels (if the user wants to simulate the evolution of oil products balance); production/ imports/ exports/ net supply of crude oil; price of crude oil, energy inputs and oil products; the discount rate, which is used to calculate the capital recovery costs of the CO_2 mitigation technologies; and possible environmental restrictions, which can be associated with the price of CO_2 emitted or with CO_2 emission caps.

The "Production" sheet reports the results of the model, including the output of oil products for each period, final energy use detailed by fuel, electricity consumption and total CO_2 emissions. The results are reported both in the form of tables and graphs.

The "Alert" sheet aims to alert about any errors found in the simulator, for example, a hydrogen balance error, which indicates that the capacity or the capacity factor of the hydrogen production unit should be reduced/increased.

The sheets called "Simulation P01, P02, P03, P04 and P05" depicts the refining scheme considered for Brazilian refineries (current and possible revamps). They are all made up of the

[2] This choice is in line with the trend of Brazilian production influenced by pre-salt streams and reduced refining of imported oil (ANP, 2017). According to GOLDEMBERG et al. (2014), the expected average API grade processed in Brazil should vary between 25 and 30 until 2030.

following units: atmospheric distillation, vacuum distillation, alkylation, atmospheric residue delayed coking, vacuum residue delayed coking, propane desasphalter, catalytic reformer, fluid catalytic cracker, hydrocracker, residue fluid catalytic cracker, hydrotreaters (naphtha, diesel, kerosene and instable products), hydrotreatment of finished gasoline, lube unit, and hydrogen generation unit (**Figure 1**). The only variables that change from one tab to the other are the processing capacities of each unit, and the yields of the atmospheric distillation unit, since they depend on the campaign applied and on the feedstock blend (**Table *2***).

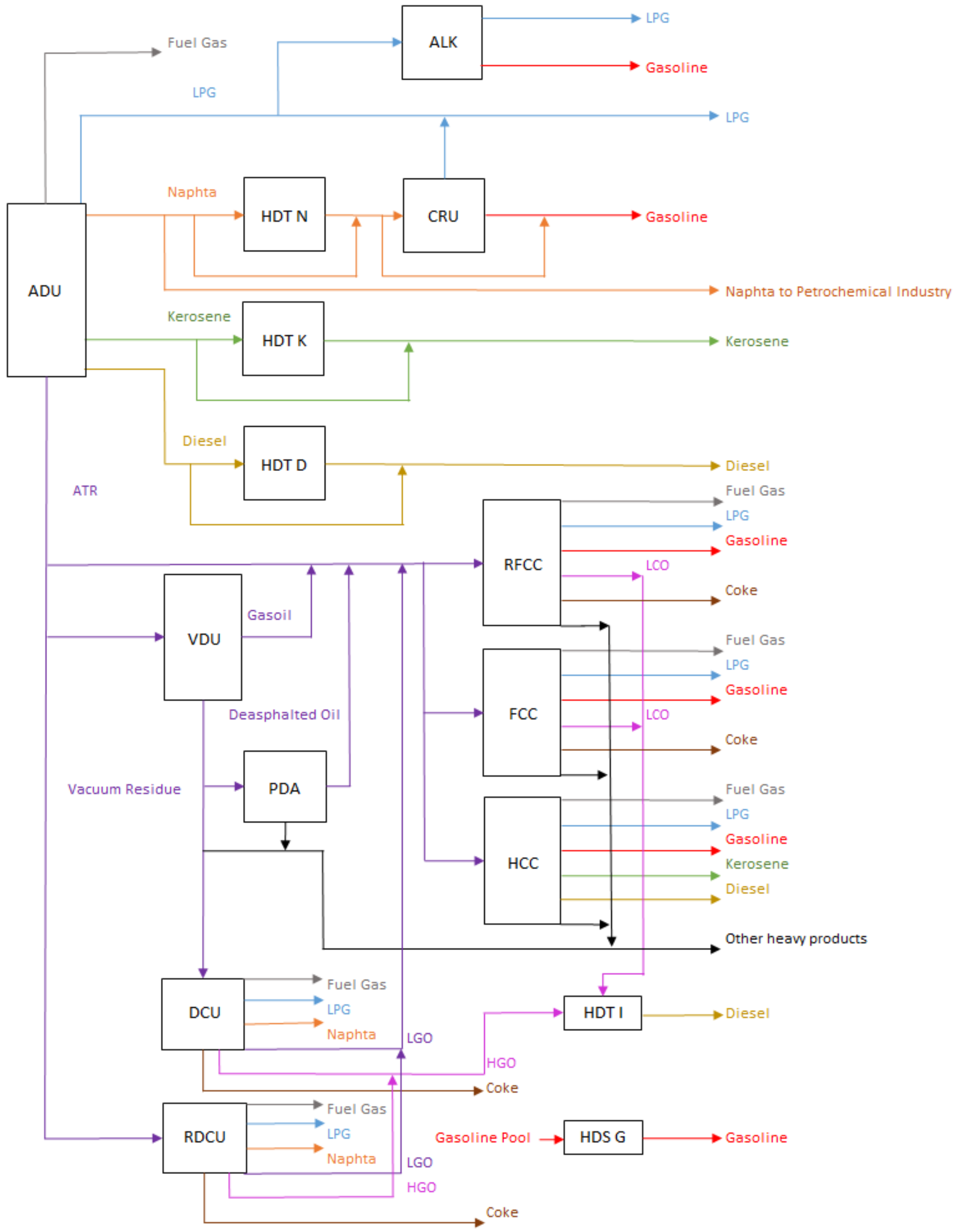

Figure 1 - Oil Refining Basic Scheme of CAESAR

Table 2 - Yields of the Atmospheric distillation unit for each type of oil (% volume)

Campaign	Product	Arabian Light	Bonny Light	Light	Medium RT	Heavy	Medium
Naphtha	**Fuel Gas (m^3 OCPE[1]/m^3 input flow)**	0.01	0.05	0.04	0.05	0.03	0.06
	LPG	1.34	1.66	2.81	0.50	0.27	1.83
	Naphtha	23.11	27.70	37.70	11.35	7.15	15.55
	Kerosene	0.00	0.00	0.00	0.00	0.00	0.00
	Diesel	41.37	49.37	45.38	42.18	41.85	37.08
	Atmospheric Residue	35.52	22.93	16.93	47.90	50.73	45.77
Kerosene	**Fuel Gas (m^3 OCPE[1]/m^3 input flow)**	0.01	0.05	0.04	0.05	0.03	0.06
	LPG	1.34	1.66	2.81	0.50	0.27	1.83
	Naphtha	17.67	22.06	30.15	8.26	5.11	11.62
	Kerosene	11.16	11.96	12.71	7.46	5.97	9.75
	Diesel	35.66	43.05	40.22	37.80	37.92	31.27
	Atmospheric Residue	35.52	22.93	16.93	47.90	50.73	45.77
Diesel	**Fuel Gas (m^3 OCPE[1]/m^3 input flow)**	0.01	0.05	0.04	0.05	0.03	0.06
	LPG	1.34	1.66	2.81	0.50	0.27	1.83
	Naphtha	17.67	22.06	30.15	8.26	5.11	11.62
	Kerosene	0.00	0.00	0.00	0.00	0.00	0.00
	Diesel	46.81	55.01	52.92	45.26	43.89	41.01
	Atmospheric Residue	35.52	22.93	16.93	47.90	50.73	45.77

Source: BARROS and SZKLO (2015); HYDROCARBON PROCESSING (2008); MEYERS (2004); GARY & HANDWERK (2001)

[1]Fuel Oil Standard Equivalent

The yields of the vacuum distillation unit vary only with the residue of atmospheric distillation unit (ATR), regardless of the chosen campaign (**Table 3**). The other processing units have fixed average yields (as shown in **Table 4**).

Table 3 - Yields of the Vacuum distillation unit (VDU) (% volume)

Product	Arabian Light	Bonny Light	Light	Medium RT	Heavy	Medium
Vacuum Gasoil	55.49	77.71	77.97	53.91	48.32	50.60
Vacuum Residue	44.50	22.59	22.03	46.09	51.68	49.40

Source: BARROS and SZKLO (2015); HYDROCARBON PROCESSING (2008); MEYERS (2004); GARY & HANDWERK (2001)

Table 4 - Yields of the process units (% volume)

Output	CRU	ALQ	FCC	RFCC	Coking	HGU (Naphtha)	HGU (Natural gas)
H_2 (Nm^3/m^3 input flow)	274.00					2,264.00	2.80
Fuel Gas (m^3 OCPE/m^3 input flow)	3.40		5.00	5.00	5.50		
FCC Coke (m^3 OCPE/m^3 input flow)			5.30	4.70			
LPG	2.60	17.00	26.00	19.30	5.20		
Naphtha			55.20	48.00	9.00		
Alkylate		83.00					
Reformate	83.00						
Kerosene							
Diesel							
LCO			18.70	18.70			
Slurry Oil			13.60	15.10			
GOLK					48.00		
GOPK					14.50		
Coke					31.10		

CRU – Catalytic reforming unit; ALQ – Alkylation unit; RFCC – Residue catalytic unit; HGU – Hydrogen generation unit; FCC – Fluid catalytic cracking; LPG – liquefied petroleum gas; LCO – Light cycle oil; GOLK – Coke light gasoil; GOPK – Coke heavy gasoil

Source: BARROS and SZKLO (2015); HYDROCARBON PROCESSING (2008); MEYERS (2004); GARY & HANDWERK (2001)

According to the typical operation of Brazilian refineries (CASTELO BRANCO et al., 2010; SZKLO, ULLER and BONFÁ, 2012; BARROS and SZKLO, 2015), the following assumptions are made:

- ATR[3] leaving the ADU must first meet all of the capacity of RFCC, then the capacity of the lubricants unit and lastly VDU capacity;
- Naphtha not transferred to petrochemicals production is hydrotreated in the HDT N unit and then delivered to the CR unit producing gasoline.
- The stream that enters the FCC is composed of the VDU heavy gasoil and heavy gasoil from the Coking unit;
- LCO produced in the RFCC and FCC units, as well as the GOLK from the Coking unit goes to the unstable pool, which in turn is routed to the HDT I unit, producing diesel . If there are unstable surplus, or if the stream sent to HDT I is greater than its capacity, these are sent to the heavy fuel oil stream;
- Diesel produced by the ADU is sent to the HDT D unit, meeting 90% of its capacity, with the remain part bypassing the hydrotreatment;

[3] ATR – Atmospheric residue

- LPG produced by the ADU is sent to the Alkylation unit, meeting 90% of its capacity, and the remaining fraction is sent to the pool of LPG, along with the LPG produced by the CR.

In the "Measures" sheet, all the fuel saving options that can be considered by the model are listed, as well as the CC technologies (see **Table 8** and **Table 9** in APPENDIX at the end of this document). They are detailed according to the processing units in which they can be implemented, their potential to reduce the specific energy consumption, the investment costs, operation and maintenance costs, penetration rates (%)[4] and final energy consumption reduction costs (the fuel saving times the fuel price). In total, 204 options of technologies are available in CAESAR. **Table 5** summarizes the distribution of technologies according to their average abatement costs and the total abatement potential, for each cost range.

Table 5 - Summary of CO_2 emissions mitigation options by cost range available in CAESAR

Cost (US$/t$CO_2$)	Number of Technologies	Abatement Potential (MtCO_2)
$C \leq 0$	15	1.4
$0 < C \leq 25$	85	143.5
$25 < C \leq 50$	6	9.4
$50 < C \leq 100$	24	205.7
$100 < C \leq 200$	49	144.5
$C \geq 200$	25	196.2

For the calculation of the CO_2 emission abatement potential in existing Brazilian refineries, penetration rates of the mitigation options were accounted for, as some of them are already implemented in the existing facilities, for the reason of being fuel saving technologies (this was the driver behind their early adoption). Those rates are quite similar to the ones found in the North American refinery system, according to Morrow III et al (2013). Furthermore, this study assumed that all technologies could effectively be implemented by the existing Brazilian refineries, i.e., there are no technical impediments[5] for their implementation.

The "Mitigation" sheet shows the simulator's estimates for the status and low-carbon scenarios in which the energy efficiency technologies and CC are implemented, in accordance with a CO_2 price defined by the user of the tool. Thus, the model compares the CO_2 price with the abatement technologies' costs and implement them according to the abatement cost curve.

[4] This depends on the current technological status of the existing refineries.

[5] A technical impediment can include lack of space or infrastructure in a unit. This leads to an impediment or, at the very least, an increase in the cost of implementing a certain abatement measure.

Basically, in the simulator tool, a Linear Programming optimization is performed, using the solver of Excel, according to the price of energy inputs, demand and supply constraints, and the cost of CO_2 (CO_2 price x emission of energy sources). For the objective-function, see equations (1.a and 1.b).

$$z = Sales - Energy\ Input\ Cost - Mitigation\ Cost - Carbon\ Cost$$

(1.a)

$$z = \sum_i Product_i \cdot Sale\ Price_i - \sum_j Energy\ Input_j \cdot Price_j - \sum_k (Inv_k \cdot CRF + OM_k) - CO_2\ Emission \cdot Price_{CO2}$$

(1.b)

Where "Sales" is the gross revenue from the refinery´s products sales (the quantity of each product "i", or "$Product_i$" times its "Sale $Price_i$" ex-taxes); "Energy Input Cost" is the total energy cost of the refinery (the quantity of each "Energy $Input_j$" times its "$Price_j$"); "Mitigation Cost" is the total cost of mitigation options listed in the model (the investment cost of each technology "k", or "Inv_k" times the capital recovery factor "CRF" (see equation 3) plus O&M costs of each technology "k", or "OM_k"); and "Carbon Cost" is the total cost of CO_2 emitted (CO_2 emissions times the price set for CO_2 emissions, or "$Price_{CO2}$").

The abatement cost of each technology was calculated as follows (equation 2):

$$AbatCost_m = \frac{(Inv_m \times CRF) + O\&M_m}{CO_2\ AvoidEmissions_m}$$

(2)

Where "Inv_m" is the investment cost of the technology "m"; "CRF" is the capital recovery factor; "$O\&M_m$" is the operations and maintenance cost of the technology "m"; "CO_2 $AvoidEmissions_m$" are the emissions avoided with the implementation of the technology "m".

Equation (3) shows the calculation of the capital recovery factor.

$$CapRec = \frac{r \times (1+r)^t}{((1+r)^t - 1)}$$

(3)

Where "r" is the discount rate[6]; "t" is the period of analysis.

Therefore, the simulator will optimize the fuel mix to meet the demand of boilers, direct heating and cogeneration. It does not include in the optimization the amount of natural gas or naphtha needed to meet the demand of the HGU. In addition, by including the cost of CO_2 associated with fuel burning (CO_2 emitted times CO_2 price), the optimization is able to find the least cost fuel mix that increases the net operational revenue under external cost internalization.

In addition, restrictions of the optimization process consist of (equations 4, 5, 6 and 7):

$$Energy\ consumption\ by\ fuel\ \geq 0 \tag{4}$$

$$Energy\ consumption\ by\ fuel\ \leq\ Energy\ supply\ by\ fuel \tag{5}$$

$$Total\ energy\ consumption = Total\ energy\ demand \tag{6}$$

$$Energy\ apparent\ production^{7} \geq\ Minimum\ demand\ that\ production\ must\ meet^{8} \tag{7}$$

Finally, the "Mitigation Graphs" sheet shows the abatement cost curve, which depicts the cumulative abatement potential of each measure ($MtCO_2$) versus its abatement cost (US$/ tCO_2).

1.1. Simulating with CAESAR

In this section, we describe the different steps of the procedure to carry out the simulation run.

Step 1 - Simulating the current Brazilian oil refinery industry to define a baseline

1) Set in the "Input" tab the refining campaign to be used in each period (naphtha, diesel or kerosene) as well as the type of HGU module (naphtha or natural gas) chosen;
2) In the tab "Scenarios", set the percentage of export and import of crude oil, the growth rates of natural gas supply and demand for oil.

[6] The discount rate used in this study was 10% p.y.

[7] These values represent the quantity of derivatives that are produced by the refinery and which is not used as an energy input.

[8] This expression represents a possible gap in the demand-side constraint that the simulation model should adopt. This gap is based on what Brazil could import or stock for the products under consideration and/ or its replacement by other products.

3) Set the discount rate, on an annual basis.
4) Set the prices of oil products, CO_2 and natural gas.
5) Implement the optimization problem to find the optimum mix of fuels to be used by the oil refinery.

From the insertion of such data, it is possible to obtain the results of energy and water consumption, output of oil products and CO_2 emissions of the oil refining industry.

Step 2 - Simulating the application of energy efficiency technologies and carbon capture on the oil refining industry

1) Enter environmental restrictions in the "Scenario" tab. As mentioned before, they can be associated with the price of CO_2 emitted, or with CO_2 emission limits. In our study, we adopted the former alternative.
2) In the "Mitigation" tab click on the “optimization” button. The fuel consumption will be optimized. Then, the tab consolidates a fuel matrix and calculates the corresponding CO_2 emissions and revenues. The water balance results are shown by the table "water calculation", both in terms of water demand and water consumption.

Lastly, the model builds automatically the emission charts, as well as the abatement cost curves for each scenario simulated.

2. WEAP

The following section details the methodology implemented for the water balance of REPLAN´s hydrographic sub-basin.

2.1. Delimitation of the study area

In this step maps of the relevant areas are loaded in WEAP from geographic information systems software. These maps contain geographical limitations of the area, fluviometric and rainfall stations, rivers and their tributaries to water catchment points, reservoirs, dams and delimitation of the area of the types of land uses to be considered.

2.2. Climatic data

The climatological data required for the Rainfall Runoff method are rainfall, crop reference evapotranspiration and crop coefficient.

In relation to the precipitation data, both the missing data and the outliers were treated by using the weighted average method. This method is based on the assumption that the missing precipitation data from a particular station is proportional to the data available for the same day or month of neighboring stations. Thus, the precipitation estimate of the missing data for a month is calculated as follows:

$$P_x = \frac{1}{n}\left[\left(P_1 \frac{N_x}{N_1}\right) + \left(P_2 \frac{N_x}{N_2}\right) + \cdots \left(P_n \frac{N_x}{N_n}\right)\right] \tag{8}$$

Where “P_x” is the missing precipitation data; “n” is the number of rainfall stations; “N” is the average annual rainfall of the historical series; “N_1,N_x” is the annual precipitation of the stations used as calculation parameter and “P_1P_n” is the monthly precipitation of the stations used as calculation parameter.

In addition, climatic data are time-series observations that need to be transformed into data corresponding to catchment areas before being integrated and used by the hydrological model. The method used was the arithmetic mean that gives each station within the catchment area an equal weight.

2.3. Identification of water demands

The demands considered to simulate the water balance are:

2.3.1. Urban Demand

The calculation of this demand follows the coefficient of volume of water consumed per person in a year. The logistic method and the growth participation projection method were used for the projection of population growth of cities using water resources from the basins inserted in the study, based on the last three demographic censuses for the years 1991, 2000 and 2010 (IBGE, 1991, 2000, 2010). In the logistic method the population growth follows a mathematical relationship that establishes an S-shaped curve, which shows the percentage growth rate proportional to the residual population. The population tends asymptotically to a saturation value (P_s). The logistic method is calculated as follows:

$$\frac{dP}{dt} = k \times P \left(\frac{P_s - P}{P}\right) \tag{9.1}$$

$$P_s = \frac{2\,(P_0 \times P_1 \times P_2) - P_1{}^2 (P_0 + P_2)}{\left(P_0 \times P_2 - P_1{}^2\right)} \qquad (9.2)$$

Where:

$$\mathrm{k} = \frac{1}{(\mathrm{t_2} - \mathrm{t_1})}\, \ell\mathrm{n} \left[\frac{\mathrm{P_0}\ (\mathrm{P_S} - \mathrm{P_1})}{\mathrm{P_1}\ (\mathrm{P_S} - \mathrm{P_0})} \right] \qquad (9.3)$$

Where "P_0" is the *p*opulation in 1991; "P_1" is population in 2000; "P_2" is population in 2010 and "P_s" is population of saturation.

The growth participation projection method, or AiBi method, was applied to cities in which the above conditions were not met. This method is AiBi is the method used by IBGE to project the total population of the Brazilian municipalities and is based on the premise that the population of a small municipality behaves linearly in relation to the population of a larger municipality or in relation to state which is located (BRITO; CAVENAGHI; JANNUZZI, 2010).

Its calculation is based on the relative difference between the population of the municipalities and that of the state in two periods in the past, in this way the relative participation of each municipality in the growth of the state is calculated (BRITO; CAVENAGHI; JANNUZZI, 2010).

This calculated proportion is multiplied by the absolute growth of the state in the period to be projected, resulting in the expected growth for each municipality, which added to the population of the base period, will result in the projected population. The equation used to design the population of a municipality in period t is as follows:

$$P_{i,t+n} = A_i \times P_{j,t+n} + B_i \qquad (10.1)$$

$$\mathrm{A_i} = \frac{(\mathrm{P_{i,t}} - \mathrm{P_{i,0}})}{(\mathrm{P_{j,t}} - \mathrm{P_{j,0}})} \qquad (10.2)$$

$$\mathrm{B_{i,t}} = \mathrm{P_{i,t}} - \mathrm{A_i} \times \mathrm{P_j} \qquad (10.3)$$

Where "$P_{(i,t+n)}$" is the population of the municipality to be projected; "$P_{(j,t+n)}$" is the projected population of the state where the municipality is located in year (t + n) ; "A_i" is the coefficient of proportionality between the growth of the municipality and the larger area and “B_i” is the linear coefficient of correction.

After calculating the number of inhabitants in each municipality, it is possible to estimate the demand for water for urban supply (Equation 11) from a per capita water consumption value that varies according to the consumption pattern of each region and should be observed separately, for each area studied.

$$Urban\ Water\ Demand\ =\ N°\ inhabitants\ \times\ water\ consumption\ per\ capita \tag{11}$$

2.3.2. Irrigation Demand

In WEAP, to calculate the need for water for irrigation, the available precipitation for evapotranspiration as well as potential crop evapotranspiration are calculated first, which are calculated as follows:

$$P_{evap} = P_{área} \times Area \times E_p \tag{12}$$

Where “P_{evap}” is the precipitation available for evapotranspiration; “P_{area}” is the average precipitation in the catchment area; “Area” is the catchment area and “E_p” is the percentage of rainfall that could be used for evapotranspiration

$$ET_p = ET_{ref} \times K_c \times Area \tag{13}$$

Where “E_{TP}” is potential evapotranspiration of culture; “ET_{ref}” is the reference evaporation of crop and “K_c” is the crop coefficient.

The need for irrigation is, then, calculated from the difference between the potential evapotranspiration value of the crops in the study area and the amount of precipitation available according to the following equation:

$$Irrigation\ Demand\ =\ max\left(\ 0, ET_p - P_{evap}\right) \tag{14}$$

The irrigation demand for the base year was obtained from land use and land cover data in geospatial vector data format of the environment secretary of São Paulo (SECRETARY OF THE ENVIRONMENT OF THE STATE OF SÃO PAULO, 2016). The data was cut to contain only the study area and then classified the different types of land use as required for use in WEAP.

The most relevant crops for the study were selected from the information on planted area calculated in geographic information systems software for the municipalities of São Paulo. Crops that presented a percentage of planted area within the catchment area higher than 3% were chosen. Thus, the relevant crops in the catchment areas are sugarcane, soybean, corn, coffee and citrus.

The reference evapotranspiration data used were obtained by the Integrated Center for Agrometeorological Information (CIIAGRO, 2016). The values considered for the catchment areas of the study derive from the arithmetic mean of the data of each municipality inserted within each of the areas (CIIAGRO, 2016).

The crop coefficient (Kc) data obtained are distinguished according to the cultivation period (initial, half, final). Since it is not possible to predict at what stage a crop is found only with planting area data, the Kcs considered in the model are the averages of the Kc values presented in the table below.

Table 6 - Crop coefficient values

Type of crop	Kc Initial	Kc half	Kc Final	Average
Pasture	0,4	0,95	0,85	0,73
Coffee	0,9	0,95	0,95	0,93
Citrus	0,75	0,7	0,75	0,73
Soy	-	1,15	0,5	0,83
Corn	-	1,2	0,45	0,83
Sugarcane	0,4	1,25	0,75	0,80

Source: ONS (2004)

According to OECD-FAO (2015), the Brazilian agricultural sector is expected to grow steadily over the next ten years, especially for crops such as oilseeds, rice, wheat, sugarcane and cotton. Land use for agriculture is expected to reach 69.4 million hectares (Mha), 20% above the average of the area used during the period 2012-14, representing a growth rate of 1.5% per year. This growth is mainly driven by the projected increase in sugarcane production, which represents approximately 37% of the projected growth for the year 2024. It is also estimated that soy will continue to dominate land use in the Brazil in the next ten years, occupying almost half of the additional area of cultivation in 2024 (OECD-FAO, 2015).

The estimated demand for irrigation between the period 2016-2040 was based on the growth rate of 1.5% of the cultivated area for sugarcane and soybean. It was obeyed the territorial limit of each municipality present in the study as follows: as the area of planting increases, the pasture area decreases in order to maintain the total of the area established in the base year.

2.3.3. Demand for animal husbandry

Water demand can be calculated from data on the number of animals per city made available by IBGE (Brazilian Institute of Geography and Statistics) and then calculate the product of the effective number of herds by a per capita coefficient of daily water consumption that is termed as Equivalent Cattle for Demand of Water - BEDA. The estimation of the demand for animal husbandry was carried out using the methodology presented in the Northeastern Integrated Water Resources Utilization Plan - PLIRHINE developed by the Superintendency of Development of the Northeast (SUDENE, 1998).

This methodology uses the product of the effective number of herds by a daily per capita coefficient that is denominated Equivalent Cattle for Water Demand - BEDA, in which the water consumption of each animal species is weighted in relation to the water demand of one Table 7. It is considered the demand of a bovine equal to 50 liters per day, that is, BEDA is equal to 50l / day.

Table 7 - Equivalent Cattle for Water Demand values

Type of Herd	BEDA	Demand per capita (l/day.BEDA)
Cattle	$\frac{BEDA}{1}$	50
Bubalinos	$\frac{BEDA}{1}$	50
Equines, Muares e Asininos	$\frac{BEDA}{1,25}$	40
Swine	$\frac{BEDA}{5}$	10
Sheep and Goats	$\frac{BEDA}{6,25}$	8
Rabbits	$\frac{BEDA}{200}$	0.25
Gallinaceous	$\frac{BEDA}{250}$	0.20

The demand of water consumed per animal is calculated according to the equation below:

$$Animal\ Husbandry\ Water\ Demand\ =\ Number\ of\ animals\ \times\ BEDA_{equivalent} \quad (15)$$

The herd data per municipality for the year 2015 were obtained from the IBGE Automatic Recovery System (SIDRA, 2015).

Meat projections for Brazil indicate growth in coming years according to the OECD (OECD-FAO, 2015) study on Brazil. The meats with the highest growth rates in the period between 2015 and 2025 are chicken meat, which has estimated annual growth of 3.0%, pork, whose projected growth for that period is 2.7% per year, and beef has a projected growth of 2.4% per year.

These percentages were used to calculate the projection of growth of livestock until the year 2025. The following years used constant values from that same year.

2.3.4. Industrial Demand

The concessions granted by the State of Sao Paulo for the withdrawal of industrial water were consulted at the Department of water and electricity of Sao Paulo. It is possible to obtain the withdrawal water volumes as well as the geographical coordinates of the water catchment point, which were both inserted at WEAP. For this specific use of water, future projections remained the same as 2015.

2.4. Other data required

"Other data" includes reservoirs for urban supply or dams used as flow regulators. For each one, it is necessary to obtain data on downstream regulated flow, its capacity, its construction year and any restrictions related to the allowed outflow for a monthly period.

2.5. Minimum Flow Requirement

The minimum river flow is defined as 50% of the lowest flow in 7 consecutive days for a 10-year return period. Depending on demand priority, a flow requirement will be met before, after or at the same time as other requirements on the river.

2.6. Baseline scenario calibration

After all climatic parameters, data on land use, reservoirs, dams, water demands and demand priorities are inserted in the model, simulations are performed in which the observed values of the fluviometric stations are compared with the flow data modeled by WEAP.

From the observed and simulated flow data, two calibration indices are calculated as suggested by the WEAP program manual. These indices are the Nash-Sutcliffe efficiency index and the BIAS index.

The efficiency coefficient of the Nash-Sutcliffe model is commonly used to evaluate the predictive power of hydrological models and is defined by the equation:

$$E = 1 - \frac{\sum_{i=1}^{n}(Q_{s,i} - Q_{o,i})^2}{\sum_{i=1}^{n}(Q_{o,i} - \bar{Q}_o)^2} \tag{16}$$

Where "E" is the Nash-Sutcliffe Coefficient; "$Q_{(s,i)}$" is the Simulated flow in year one period; "$Q_{(o,i)}$" is the observed flow in one period; "$\overline{Q}_o$" is the average flow observed during the period considered and n is the number of years.

According to (PEREIRA et al., 2016) the value of E equals 1 means perfect fit of the data predicted by the model; if E is bigger than 0.75, the model is adequate and good; if E is between 0.36 and 0.75 the model is considered satisfactory. However, if E is smaller than 0.36, the model is not satisfactory. The coefficient of efficiency is sensitive to extreme values and may result in sub-optimal results when the dataset contains large outliers in it.

The BIAS index is defined by the equation:

$$P_{BIAS} = 100 \times \left[\frac{(\overline{Q_s} - \overline{Q_o})}{\overline{Q_o}}\right] \tag{17}$$

Where "P_{BIAS}" is the value of BIAS index; "$\overline{Q_s}$" is the average of simulated flows during the period considered and "$\overline{Q_o}$" is the average of observed flows during the period considered.

The P_{BIAS} is the percentage value of bias of the simulated flows in relation to the observed flows. The nearer to zero is this value, the better the model will represent reality, ie the smaller the trend in the estimates. For values of $| P_{BIAS} |$ smaller than 10%, the model is considered very good; between values of $10\% < | P_{BIAS} | < 15\%$, the model is good; $15\% < | P_{BIAS} | < 25\%$, the model is satisfactory and $| P_{BIAS} | > 25\%$, the model is inadequate (MORIASI et al., 2007).

2.7. Result Analysis

After the model has been calibrated, the first analysis is the verification of the water demand for REPLAN. Then, the flow observation point defined by the water management policies is analysed to observe if during the period of study there can be the occurrence of limitation of flow.

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APPENDIX

Table 8 – Parameters of CO_2 mitigation technologies

Unit	Technology	Fuel (%)	Steam (%)	Electricity (%)	H2 Demand (%)	Investment (US$/bbl/y)	O&M (US$/y/bbl)	Penetration rate	Cost (US$/GJ)
ADU	Reduce Stand-By Boiler Requirements		2%			0.48	-0.90	50%	-1.90
ADU	Heat storage reduction between ADU and VDU		3%			1.16	-0.42	50%	-0.47
ADU	Condensate recovery		0%	0%		0.02	0.00	90%	0.01
ADU	Reduction of boiler make-up water with condensate treatment		20%			8.76	0.08	50%	0.47
ADU	Addition of steam recycle with steam ejector at VDU		18%			31.39	0.11	80%	0.75
ADU	Integration of the gas processing unit with ADU		6%	1%		25.66	0.04	80%	1.87
ADU	Improvements in steam insulation maintenance		2%			3.86	0.03	50%	1.97
ADU	Steam fouling reduction		40%	13%		7.88	12.10	40%	2.45
ADU	Reduction of coke formation in ADU furnace passes	8%				8.55	13.14	60%	3.19
ADU	Installation of vacuum pumps to replace steam ejectors		57%			889.52	3.10	90%	3.31
ADU	Efficient burners/ control of air excess in the ADU	9%				89.62	0.81	50%	3.91
ADU	Installation of chillers at the top of the ADU column to reduce the thermal load of the capacitor			2%		0.43	0.00	40%	5.82
ADU	Installation of air preheaters in ADU ovens			1%		0.28	0.00	0%	9.84
ADU	Increased insulation of steam lines		18%	4%		84.89	0.76	0%	10.47
ADU	Revamp in the integration of heat in the ADU			1%		0.31	0.01	0%	11.44
ADU	Installation of efficient internals at VDU	3%		5%		48.05	0.43	0%	11.70
ADU	Reduction of air infiltration in the ADU (insulation)	2%				33.32	0.12	0%	11.72
FCC	Condensate recovery		1%			3.98	-1.39	50%	-0.47

FCC	Reduction of boiler make-up water with condensate treatment		5%		23.89	0.21	50%	0.47
FCC	Improvements in steam insulation maintenance		0%		12.83	0.12	50%	3.03
FCC	Revamp in FCC heat integration (low cost)			6%	69.38	1.32	40%	3.22
FCC	Revamp in FCC heat integration (high cost)			2%	64.17	1.22	0%	13.68
FCC	Replace steam drive with electrical drive		33%	-3%	1380.26	4.81	50%	4.11
FCC	Installation of regenerative tower - HRSG Regenerator		306%		27404.93	95.47	70%	5.14
FCC	Installation of CO-kiln in regenerative tower HRSG		68%		4871.47	16.97	40%	8.22
FCC	Increased insulation of steam lines		0%		0.07	0.00	0%	9.73
FCC	Installation of new FCC internals			4%	97.21	0.87	0%	10.53
FCC	Installation of top chillers in the FCC			1%	53.44	0.19	0%	15.05
DCU	Reduce Stand-By Boiler Requirements		-2%		3.39	-6.36	50%	-1.90
DCU	Steam recovery		-2%		7.96	-2.79	50%	-0.47
DCU	Reduction of boiler make-up water with condensate treatment		-13%		57.73	0.52	50%	0.47
DCU	Increased insulation of steam lines		0%		18.13	0.16	50%	4.28
DCU	Reduction of coke formation on DCU piping surfaces	14%	0%		178.01	273.47	60%	5.18
DCU	Efficient furnace installation/ air control	15%			1855.64	16.67	50%	6.35
DCU	Revamp in the DCU heat integration (low cost)		-33%	10%	2051.91	38.92	40%	7.97
DCU	Revamp in the DCU heat integration (high cost)		-10%	3%	878.94	16.67	0%	19.03
DCU	Installation of new DCU internals	0%		7%	79.59	0.72	0%	10.41
DCU	Installation of air preheaters in DCU ovens	9%			1144.58	10.28	0%	12.57
DCU	Installation of top chillers in the DCU	9%		6%	1698.70	5.92	0%	17.02
DCU	Revamp in the steam distribution		0%		20.17	0.18	0%	19.05
DCU	Reduction of air infiltration in the DCU (increased insulation)	3%			738.76	6.64	0%	24.06
CRU	Reduce Stand-By Boiler Requirements		0%		0.68	-1.27	50%	-1.90
CRU	Recover Blowdown Steam		0%		1.59	-0.56	50%	-0.47
CRU	Reduce hot rundown		0%		0.00	0.00	90%	0.00
CRU	Reduce Boiler Blowdown/Water Treatment		-4%		12.21	0.11	50%	0.47
CRU	Reduce Background Flaring				0.00	0.00	20%	0.86

CRU	Integrate GPU w/ISBL Units		-3%	0%		92.31	0.83	80%	1.97
CRU	Improved Maintenance/Steam Lines & Traps		0%			1.75	1.20	50%	2.95
CRU	Revamp CRU Heat Integation (lowcost)	2%		0%		258.39	0.45	40%	3.66
CRU	Reduce Coking of CRU Tube Surfaces	1%				58.27	39.86	80%	4.76
CRU	Revamp GPU Heat Integation		0%	0%		0.00	0.00	40%	5.22
CRU	Efficient CRU Burners/Control X Air	3%				631.94	5.69	50%	5.83
CRU	Increase Steam Line Insulation		-1%			29.55	0.56	0%	11.05
CRU	Install CRU Furnace Air Pre-Heat	8%				1947.96	17.53	0%	11.54
CRU	Install New CRU Internals	4%		1%		1009.16	9.08	0%	13.44
CRU	Install New GPU Internals		0%	0%		0.01	0.00	0%	14.69
CRU	Install CRU Overhead Chillers	4%		-1%		1210.62	4.22	0%	15.63
CRU	Install GPU Overhead Chillers		0%	0%		0.01	0.00	0%	17.08
CRU	Revamp CRU Heat Integration (highcost)	4%		1%		1367.00	2.36	0%	17.47
CRU	Revamp Steam Distribution/Reduce Pressure Drop		-2%			102.90	1.96	0%	17.49
CRU	Insulation/Reduce CRU Air Infiltration	3%				1240.53	23.57	0%	22.09
HDSG	Reduce Stand-By Boiler Requirements		4%			1.14	-2.15	50%	-1.90
HDSG	Recover Blowdown Steam		1%			0.67	-0.24	50%	-0.47
HDSG	Install SRU Waste Heat Boiler		2%			0.01	0.00	90%	0.00
HDSG	Install PSA to recover high-purity H2			0%	3%	0.00	0.00	80%	0.00
HDSG	Reduce Boiler Blowdown/Water Treatment		33%			19.66	0.18	50%	0.47
HDSG	Integrate GPU w/ISBL Units		1%	0%		5.86	0.01	80%	1.97
HDSG	Integrate AGR w/ISBL Units		15%	0%		119.26	0.21	80%	2.36
HDSG	Increase AGR Solvent Concentration		36%	0%		11.39	17.52	50%	2.37
HDS	Integrate SWS w/ISBL Units			0%		73.08	0.13	80%	2.95

G									
HDSG	Revamp HTU Heat Integation (lowcost)		36%	1%		130.80	2.49	40%	3.63
HDSG	Improved Maintenance/Steam Lines & Traps		1%			1.56	1.07	50%	3.90
HDSG	Replace Steam Drives w/Elec on Rec Compressors		64%	-1%		307.29	2.77	40%	4.52
HDSG	Reduce Coking of HTU Tube Surfaces	2%				10.87	16.72	50%	4.72
HDSG	Efficient HTU Burners/Control X Air	1%				93.59	0.84	50%	5.79
HDSG	Revamp GPU Heat Integation			0%		0.00	0.00	40%	6.15
HDSG	Improve catalysts to reduce H2 consumption			1%	24%	1015.36	9.14	0%	7.39
HDSG	Install HTU Furnace Air Pre-Heat	5%				288.51	2.60	0%	11.45
HDSG	Increase Steam Line Insulation		4%			33.00	0.30	0%	11.57
HDSG	Install New HTU Internals	9%		2%		653.24	5.88	0%	13.34
HDSG	Install New GPU Internals		0%			0.00	0.00	0%	14.57
HDSG	Install HTU Overhead Chillers			-3%		365.10	1.27	0%	15.51
HDSG	Install GPU Overhead Chillers			0%		0.00	0.00	0%	16.95
HDSG	Revamp HTU Heat Integation (highcost)		18%			187.44	3.56	0%	17.34
HDSG	Revamp Steam Distribution/Reduce Pressure Drop		4%			39.09	0.74	0%	17.36
HDSG	Insulation/Reduce HTU Air Infiltration	1%				172.08	0.60	0%	21.93
HDTD	Reduce Stand-By Boiler Requirements		2%			0.62	-1.18	50%	-1.90
HDT	Recover Blowdown Steam		2%			1.71	-0.60	50%	-0.47

D									
HDT D	Install SRU Waste Heat Boiler		1%			0.00	0.00	90%	0.00
HDT D	Install PSA to recover high-purity H2			0%	2%	0.00	0.00	80%	0.00
HDT D	Reduce Boiler Blowdown/Water Treatment		13%			11.01	0.10	50%	0.47
HDT D	Integrate GPU w/ISBL Units		1%	0%		8.21	0.07	80%	1.97
HDT D	Integrate AGR w/ISBL Units		4%	0%		46.10	0.08	80%	2.36
HDT D	Increase AGR Solvent Concentration		10%	0%		4.29	6.60	50%	2.37
HDT D	Revamp HTU Heat Integation (lowcost)		61%	1%		198.71	1.79	0%	3.67
HDT D	Improved Maintenance/Steam Lines & Traps		1%			1.30	0.89	50%	3.94
HDT D	Replace Steam Drives w/Elec on Rec Compressors		48%	0%		320.04	2.88	40%	4.52
HDT D	Reduce Coking of DTU Tube Surfaces	1%				11.53	17.74	50%	4.78
HDT D	Efficient DTU Burners/Control X Air	1%				100.51	0.90	50%	5.85
HDT D	Revamp GPU Heat Integration		0%	0%		0.00	0.00	40%	6.15
HDT D	Improve catalysts to reduce H2 consumption			0%	14%	634.83	5.71	0%	7.39
HDT D	Install DTU Furnace Air Pre-Heat	3%				307.47	2.77	0%	11.58
HDT D	Increase Steam Line Insulation		2%			24.37	0.22	0%	11.70
HDT D	Install New DTU Internals	5%		1%		540.80	4.87	0%	13.49
HDT D	Install New GPU Internals		0%	0%		0.00	0.00	0%	14.74
HDT	Install DTU Overhead Chillers	3%		-2%		379.18	1.32	0%	15.69

D									
HDT D	Install GPU Overhead Chillers			0%		0.00	0.00	0%	17.14
HDT D	Revamp DTU Heat Integation (highcost)		13%	0%		198.98	3.78	0%	17.54
HDT D	Revamp Steam Distribution/Reduce Pressure Drop		2%			34.64	0.66	0%	17.56
HDT D	Insulation/Reduce DTU Air Infiltration	1%				190.59	0.67	0%	22.18
HDT Q	Reduce Stand-By Boiler Requirements		1%			0.67	-1.26	50%	-1.90
HDT Q	Recover Blowdown Steam		1%			1.58	-0.55	50%	-0.47
HDT Q	Install SRU Waste Heat Boiler		0%			0.00	0.00	90%	0.00
HDT Q	Reduce Boiler Blowdown/Water Treatment		9%			12.72	0.24	50%	0.47
HDT Q	Integrate GPU w/ISBL Units		0%	0%		3.45	0.01	80%	1.97
HDT Q	Integrate AGR w/ISBL Units		3%	0%		61.99	0.11	80%	2.36
HDT Q	Increase AGR Solvent Concentration		7%	0%		5.87	9.03	50%	2.37
HDT Q	Revamp KTU Heat Integation (lowcost)		45%	1%		307.08	2.76	0%	4.25
HDT Q	Replace Steam Drives w/Elec on Rec Compressors		49%	-17%		584.68	5.26	40%	4.52
HDT Q	Improved Maintenance/Steam Lines & Traps		1%			1.61	1.10	50%	4.56
HDT Q	Reduce Coking of KTU Tube Surfaces	1%				223.01	2.01	50%	5.53
HDT Q	Revamp GPU Heat Integation		0%	0%		0.00	0.00	40%	6.15
HDT Q	Efficient KTU Burners/Control X Air	1%				205.07	1.85	50%	6.78
HDT	Improve catalysts to reduce H2 consumption			0%	4%	282.34	5.36	0%	7.39

Q									
HDTQ	Install KTU Furnace Air Pre-Heat	3%				630.93	5.68	0%	13.41
HDTQ	Increase Steam Line Insulation		1%			22.77	0.20	0%	13.55
HDTQ	Install New KTU Internals	3%		1%		787.41	7.09	0%	15.62
HDTQ	Install New GPU Internals		0%	0%		0.00	0.00	0%	17.07
HDTQ	Install KTU Overhead Chillers	3%		-2%		787.34	2.75	0%	18.17
HDTQ	Revamp KTU Heat Integation (highcost)		14%	0%		443.66	3.99	0%	20.31
HDTQ	Revamp Steam Distribution/Reduce P Drop		1%			34.16	0.31	0%	20.33
HDTQ	Install GPU Overhead Chillers			0%		0.00	0.00	0%	20.95
HDTQ	Insulation/Reduce KTU Air Infiltration	1%				367.92	6.99	0%	25.68
HDTQ	Install PSA to recover high-purity H2			0%	2%	564.22	1.97	0%	32.55
HDTN	Reduce Stand-By Boiler Requirements		1%			0.15	-0.28	50%	-1.90
HDTN	Recover Blowdown Steam		1%			0.53	-0.19	50%	-0.47
HDTN	Install SRU Waste Heat Boiler		0%			0.00	0.00	90%	0.00
HDTN	Reduce Boiler Blowdown/Water Treatment		6%			3.19	0.06	50%	0.47
HDTN	Integrate GPU w/ISBL Units		1%	0%		4.65	0.01	80%	1.97
HDTN	Integrate AGR w/ISBL Units		1%	0%		5.57	0.01	80%	2.36
HDTN	Increase AGR Solvent Concentration		2%	0%		0.57	0.87	50%	2.37
HDT	Revamp NTU Heat Integation (lowcost)		95%	0%		189.26	1.70	0%	3.53

NHDT	Improved Maintenance/Steam Lines & Traps		1%			2.86	0.03	50%	3.79
NHDT	Replace Steam Drives w/Elec on Rec Compressors		64%	-1%		57.49	39.32	40%	4.52
NHDT	Reduce Coking of NTU Tube Surfaces	3%				142.11	1.28	50%	4.59
NHDT	Efficient NTU Burners/Control X Air	2%				13.85	21.31	50%	5.62
NHDT	Revamp GPU Heat Integation		0%	0%		0.00	0.00	40%	6.15
NHDT	Improve catalysts to reduce H2 consumption			0%	5%	169.18	3.21	0%	7.39
NHDT	Increase Steam Line Insulation		1%			4.02	0.04	0%	10.65
NHDT	Install NTU Furnace Air Pre-Heat	7%				403.43	3.63	0%	11.13
NHDT	Install New NTU Internals	7%		0%		474.66	4.27	0%	12.96
NHDT	Install New GPU Internals		0%	0%		0.00	0.00	0%	14.16
NHDT	Install NTU Overhead Chillers	7%		-1%		498.93	1.74	0%	15.07
NHDT	Install GPU Overhead Chillers			0%		0.00	0.00	0%	16.47
NHDT	Revamp KTU Heat Integation (highcost)		29%	0%		273.57	2.46	0%	16.85
NHDT	Revamp Steam Distribution/Reduce P Drop		1%			6.37	0.06	0%	16.87
NHDT	Insulation/Reduce NTU Air Infiltration	2%				220.95	4.20	0%	21.30
NHDT	Install PSA to recover high-purity H2			0%	2%	342.31	1.19	0%	32.55
NHDT	Reduce Stand-By Boiler Requirements		2%			0.94	-1.76	50%	-1.90
IHDT	Recover Blowdown Steam		2%			2.57	-0.90	50%	-0.47

I HDT	Install SRU Waste Heat Boiler		1%			0.00	0.00	90%	0.00
I HDT	Install PSA to recover high-purity H2			0%	1%	0.00	0.00	80%	0.00
I HDT	Reduce Boiler Blowdown/Water Treatment		16%			16.52	0.15	50%	0.47
I HDT	Integrate GPU w/ISBL Units		1%	0%		12.31	0.11	80%	1.97
I HDT	Integrate AGR w/ISBL Units		5%	0%		69.14	0.12	80%	2.36
I HDT	Increase AGR Solvent Concentration		12%	0%		6.43	9.89	50%	2.37
I HDT	Revamp HTU Heat Integation (lowcost)		73%	1%		298.07	2.68	0%	3.67
I HDT	Improved Maintenance/Steam Lines & Traps		1%			1.94	1.33	50%	3.94
I HDT	Replace Steam Drives w/Elec on Rec Compressors		57%	0%		480.06	4.32	40%	4.52
I HDT	Reduce Coking of DTU Tube Surfaces	2%				17.29	26.61	50%	4.78
I HDT	Efficient DTU Burners/Control X Air	1%				150.76	1.36	50%	5.85
I HDT	Revamp GPU Heat Integration			0%		0.00	0.00	40%	6.15
I HDT	Improve catalysts to reduce H2 consumption			0%	9%	952.24	8.57	0%	7.39
I HDT	Install DTU Furnace Air Pre-Heat	4%				461.21	4.15	0%	11.58
I HDT	Increase Steam Line Insulation		3%			36.55	0.33	0%	11.70
I HDT	Install New DTU Internals	5%		1%		811.20	7.30	0%	13.49
I HDT	Install New GPU Internals		0%	0%		0.00	0.00	0%	14.74
I HDT	Install DTU Overhead Chillers	3%		-2%		568.75	1.98	0%	15.69

I								
HDT I	Install GPU Overhead Chillers			0%	0.00	0.00	0%	17.14
HDT I	Revamp DTU Heat Integation (highcost)		16%	0%	298.47	5.67	0%	17.54
HDT I	Revamp Steam Distribution/Reduce Pressure Drop		3%		51.97	0.99	0%	17.56
HDT I	Insulation/Reduce DTU Air Infiltration	1%			285.89	1.00	0%	22.18

ADU – Atmospheric distillation unit; FCC – Fluid catalytic cracking; DCU – Delayed coking unit; CRU – Catalytic reforming unit; HDS G– Gasoline hydrodesulphurization unit; HDT D – Diesel hydrotreatment unit; HDT Q – Kerosene hydrotreatment unit; HDT N – Naphtha hydrotreatment unit;; HDT I – Severe hydrotreatment unit

Source: Based on SCHAEFFER et al. (2015); MORROW III et al. (2013); SCHAEFFER et al. (2012); WORREL and GALITSKY (2005)

Table 9 - Parameters of Carbon Capture technologies

Unit	Technology	BFW (t/tCO_2)	CW (t/tCO_2)	Steam (TJ/tCO_2)	Electricity (kWh/tCO_2)	Efficiency (%)	Abatement Potential ($MtCO_2$)	Penetration Rate (%)	Investment Cost (US$/$tCO_2$)	O&M (US$/$tCO_2$/year)	Abatement Cost (US$/$tCO_2$)
HGU	**Capture HGU - SMR/MDEA**	0.31	0.45	3.7	108.0	99.0	102.1	100	118.3	11.3	23.4
FCC	**Capture FCC - Oxyfiring**	0.0	0.15	0.0	210.0	59.0	174.4	100	285.0	45.0	74.1

HGU – Hydrogen generation unit; FCC – Fluid catalytic cracking

Source: Based on ROCHEDO et al. (2016); LINDSAY et al. (2009); MELLO et al. (2009)