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Abstract

Oil refineries are major CO_2 emitters and are usually located in water-stress sites. While some CO_2 mitigation options can reduce water withdrawals, others can increase it, and still others are neutral. By simulating two parametric models, one for all Brazilian refineries, and the other locally detailing the water balance of the country´s largest refinery, this study aimed to quantify the impacts of CO_2 mitigation options on the water use of oil refineries. Findings show that, at 25 and 100 US\$/tCO_2, Brazilian refineries can abate CO_2 emissions by 10% and 26%, respectively, compared to current emissions. A relevant share of this abatement derives from the implementation of carbon capture facilities in fluid catalytic cracking and hydrogen generation units. However, these CC facilities offset the co-benefits of other CO_2 mitigation options that can reduce steam and cold water requirements in refineries. In fact, for the largest Brazilian oil refinery, the implementation of all mitigation measures had almost no effect on its water balance. This means that CO_2 abatement in refineries has no significant impact on water consumption (no negative trade-off). However, this also means that the water stress in oil refineries should be dealt with with measures not directly linked to CO_2 abatement (no significant co-benefits).

Keywords: Climate-energy-water nexus; oil refineries; Brazil.

1. Introduction

Two of the UN Sustainable Development Goals (SDGs) focus on achieving physical and economic access to energy and water in quantity and quality. SDG7 aims to provide affordable, secure, sustainable and modern energy for all; furthermore, SDG6 aims to provide available and sustainable management of water and sanitation for all (UN, 2016). Energy and water are key elements closely linked to all other sectors within an economy. They also interact closely in many aspects (BIGGS et al., 2015). In this way, achieving the goal of a natural resource will influence the fulfillment of the other goal. For instance, water is needed at all stages of energy

production, while water management, treatment and transportation require energy. Moreover, global climate change can add a significant amount of uncertainty to these complex inter-relations. Changes in climate variables, such as precipitation and temperature, can affect water and energy resources, increasing their vulnerabilities. Also, the strategies to tackle climate change by reducing (mitigating) greenhouse-gas (GHG) emissions can affect the water-energy nexus (HOWELLS et al., 2013).

For instance, coal-fired thermoelectric plants need water resources, mainly for cooling processes. For these plants, a promising GHG mitigation option could be the installation of amine-based carbon capture (CC) systems (ROCHEDO and SZKLO, 2013). However, CC would also increase both water withdrawal and consumption by the thermoelectric plant by more than 100%, which may intensify its vulnerability and affect the water supply to other users downstream from the power plant (ZHAI and RUBIN, 2011; MERSCHMANN et al., 2012). In the case of the production of liquid biofuels, the nexus goes beyond the energy conversion facility, which may also be affected by CO_2 mitigation options, and mostly refers to the biomass production, which usually represents a significant share of water consumption (irrigation) in countries such as Brazil (IEA, 2016). Interestingly enough, the increase of biomass productivity arising from irrigation is an emblematic case of the tradeoff between GHG mitigation and water.

At the end, given all these complex and interconnected relationships, an integrated analysis is needed to evaluate the nexus between energy-water under the challenges associated with climate change (HOWELLS et al., 2013). In addition, each energy sector needs a proper analysis to quantify this nexus. For this study, this analysis is performed at both country and local level. On one hand, the country level provides the basic answer for the primary research question of this study, which is: do CO_2 mitigation options affect the water consumption of an oil refinery system (or even: what could the nexus be between the carbon mitigation cost curve and the water consumption in refineries)? On the other hand, the detailed local level analysis, whose focus is on a specific oil refinery, allows the answering of the secondary question of this study, which is: do the impacts of climate mitigation options on water consumption affect the water supply-demand balance of an oil refinery? Only local level analyses can solve this secondary question, since it requires the proper evaluation of water sources (water supply) and sinks (water users).

In fact, oil refining is an energy-intensive activity, whose greenhouse gas (GHG) emissions are closely related to the combustion and chemical conversion of fossil fuels. The fuel combustion in oil refineries is related to the generation of direct heat, process steam and even electricity, all in stationary sources. The refineries´ technological schemes are complex (GOMES et al., 2009; COELHO and SZKLO, 2015), depending on the characteristics of the feedstocks, the units'

capacities, the production profile of the oil products (quantities and specifications), and the choice of technologies to be used (CASTELO BRANCO et al., 2011). For instance, refineries that process heavy crude oils to output light products present process schemes that use more final energy, and in turn emit more GHG (EPA, 2010). In addition, the more stringent the oil derivative specifications, the greater the energy and water consumption of the refining process, due to the need of severe hydro-treatment units, which use the hydrogen produced in units emitting CO_2 from the steam reforming of light hydrocarbons (SZKLO and SCHAEFFER, 2007; CONCAWE, 2012; SUN et al., 2018). In 2012, oil refineries accounted for 2.7% of US, 3.2% of European Union and 2.0% of Brazil CO_2 emissions (MCTI, 2013; PETROBRAS, 2013; EPA, 2014).

Nevertheless, the vast majority of the research associated with the nexus between energy and climate in oil refineries has focused on the trade-off between fuel specifications and CO_2 emissions (CONCAWE, 2000; CHAN, 2006; SZKLO AND SCHAEFFER, 2007; JOHANSSON et al., 2012; CONCAWE, 2012). In the case of the nexus between energy and water, there are some studies on the relationship between water consumption and energy use in oil refineries (HIGHTOWER and PIERCE, 2008; IPIECA, 2010; HWANG and MOORE, 2011; PAN et al., 2012; MUGHEES and AL-AHMAD, 2014; SUN et al., 2018). Previous research has also focused on the implementation of CO_2 capture in oil refineries and its abatement cost, as ROCHEDO et al. (2016) have done, but it has failed to explore the water nexus with CO_2 mitigation options in oil refineries.

At the end, few attempts have been made to quantify the relationship between climate (CO_2 emission mitigation) and water-energy use in oil refineries. **Table 1** provides a brief summary of the opportunities for CO_2 abatement measures in oil refineries' processing units, and their likely impact on water consumption. It highlights the signs of the impacts that are quantified later in this study (positive and negative signs) through the use of simulation tools for all Brazilian refineries and for a specific refinery in detail.

Table 1 – Qualitative Impacts on Water Consumption of CO_2 Mitigation Options in Oil Refineries

Process Unit	Heat Integration	Reduce Boiler Blowdown/Water Treatment	Improved Maintenance/Steam Lines & Traps	Reduce Stand-by Boiler Requirements	Increase Steam Line Insulation	Recover Blowdown Steam	CC
ADU	-	-	-	-	-		
VDU	-	-	-	-	-		
CRU		-		-		-	
HDT	-	-	-	-	-	-	

RFCC	-	-		
FCC	-	-		+
DCU	-	-	-	
HGU				+

Note: The positive sign means that the measure has a positive impact on water consumption, ie it helps to reduce this consumption. On the other hand, the negative sign has a negative impact, indicating an increase in water consumption with the application of the measure.

ADU – atmospheric distillation unit; VDU – vacuum distillation unit; CRU – catalytic reforming unit; HDT – hydrotreatment unit; RFCC – resid fluid catalytic cracking; FCC – fluid catalytic cracking; DCU – delayed coking unit; HGU – hydrogen generation unit; CC: CO_2 capture

Source: WORREL and GALITSKY (2003); WORREL and GALITSKY (2005); CONCAWE (2008); BERGH, 2012; MORROW III et al. (2013)

Regarding water use, oil refining requires considerable amounts of water, which vary significantly between refineries, depending on the process configuration (WU and CHIU, 2011; SUN et al., 2018), the petroleum specification (e.g., density, sulphur content, total acid number) (SUN et al., 2018), and the products' requirements. Within this context, in Brazilian refineries, water requirements deserve attention due to the processing of heavy-to-medium crude oils, as well as to the increasingly stringent specifications of fuels that require the implementation of hydrotreatment units, associated with the water-intensive steam reforming process (CASTELO BRANCO et al., 2010; SZKLO, ULLER and BONFÁ, 2012; BARROS and SZKLO, 2015)[1].

In addition, in Brazil, water availability is not evenly distributed. While the northern region holds more than 80% of all water availability, the basins located in large urban centers, in the Brazilian southeast, for example, are currently facing low water availability coupled with high withdrawals. As shown in **Figure 1**, most Brazilian refineries are already dealing with water stress, measured in relation to the level of water criticality of watersheds. This index measures the ratio between water withdrawals for consumptive uses (irrigation, water supply, urban and industrial) and the water availability of each sub-basin expressed through the value of average flow with permanence of 95%. In fact, REPLAN, REVAP, RLAM and REDUC, which account

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[1]In 2018, the Brazilian oil refining industry consisted of 17 refineries in operation, with a total installed nominal capacity of 2.2 Mbbl/day (ANP, 2018). Most Brazilian refineries were built before the 1980s with the objective of meeting the demand for gasoline and fuel oil in major urban centers (also close to Brazil's coast). However, due to the increasing diesel demand after the 1980s (BORBA et al., 2017), as well as the ramp up of medium-to-heavy crude oil production in Brazilian offshore basins in the 1980s and 1990s (HALLACK et al., 2017), the refining schemes of existing refineries were altered to convert the heaviest fractions of crude into medium cuts – e.g., by adding delayed coking units and severe hydrotreatment processes (which remove nitrogen compounds, high sulfur compounds and aromatic rings) (SZKLO and SCHAEFFER, 2007; SZKLO et al., 2012).

121 for 54% of Brazil's refining capacity, are located in areas classified as having critical water
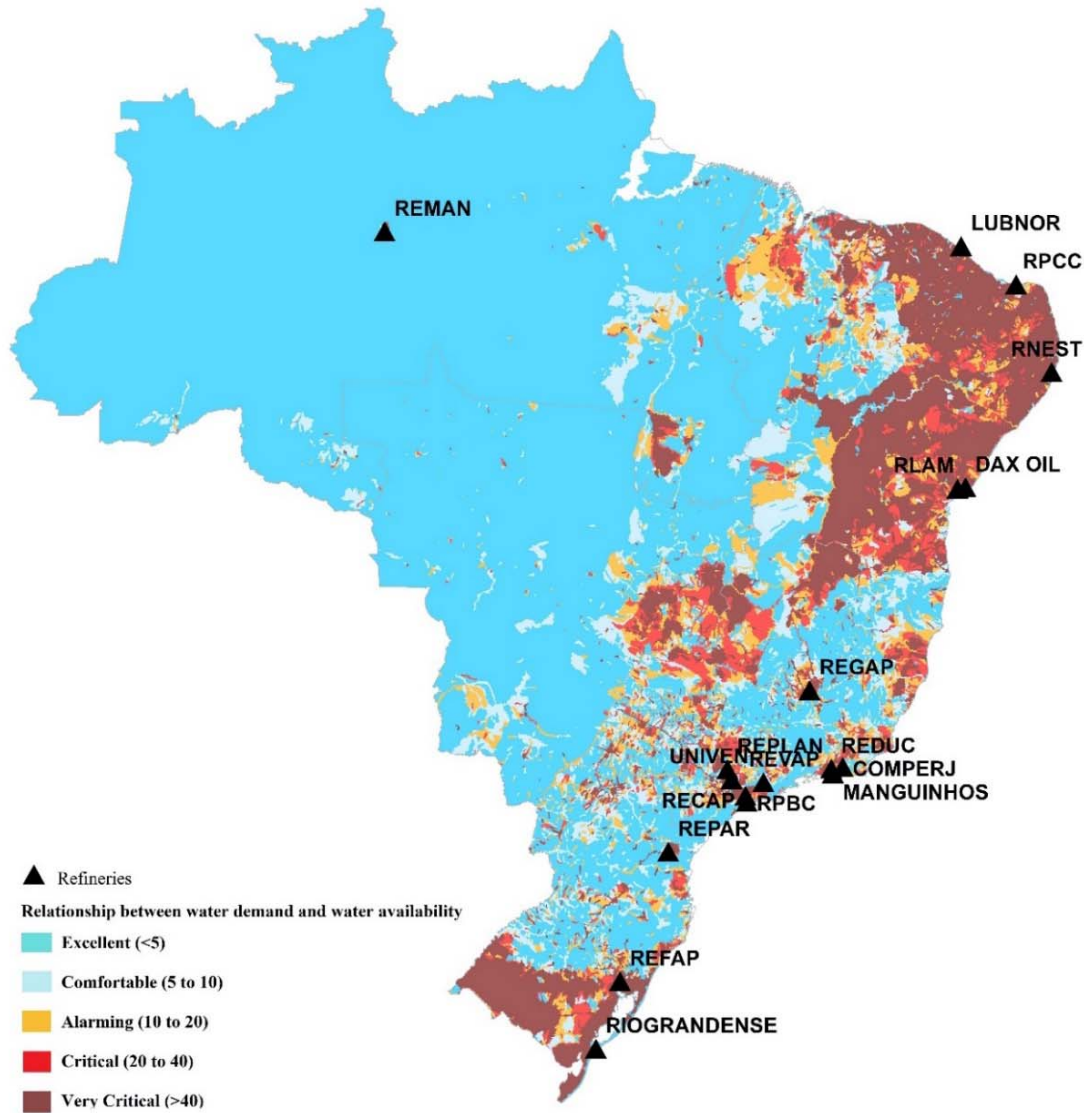122 availability.

123

124
125 **Figure 1 - Refineries locations and water criticality indicator of sub-basins in Brazil**

126 Source: Based on ANA (2017)

127

128 To sum up, oil refineries are major CO_2 emitters and are usually located in sites with already
129 critical availability supply of water. This is the case for Brazil, but it can be seen worldwide
130 (OIL and GAS JOURNAL, 2018). Some CO_2 emission mitigation measures can positively or
131 negatively influence both withdrawal and water consumption at refineries. Within this context,
132 this study aims to quantify the extent to which these measures can impact refineries' water use.
133 First, by developing an energy, CO_2, H_2, water balance simulator for Brazilian oil refineries, and

applying it to different scenarios of CO_2 mitigation, this study evaluates the CO_2 mitigation-energy-water nexus at the country level. Then, this study analyzes the water supply of the hydrographic basin in which the largest Brazilian refinery, REPLAN, is located and how it behaves over time. This detailed analysis, at a local level, not only quantifies the water withdrawal impacts of CO_2 mitigation options, but also identifies whether or not these impacts could be overcome by the current water supply of this specific refinery.

The next section presents the methodology used to carry out the analysis, as well as a brief description of the simulation tools applied. Section 3 discusses the results obtained. Lastly, the final remarks of the study, highlighting also its limitations, are presented.

2. Methods

2.1. Methodological Procedure

The methodological procedure applied by this study consisted of the following steps. The first step is the definition of GHG mitigation measures in oil refineries, according to the scientific literature and the experience of the authors regarding Brazil's oil refineries[2]. Then, the study simulates the baseline case for estimating the scenario without CO_2 mitigation, and simulates the impacts of introducing CO_2 price scenarios into oil refineries, in terms of CO_2 emissions, final energy use and water consumption. This provides the carbon mitigation cost curve, and also helps to identify (quantify) the impacts of GHG mitigation options on the water consumption for all Brazilian refineries. However, this step is not able to detail the water supply balance at a local level. Therefore, using the mitigation cost curve for Brazilian refineries (mentioned above), the proposed procedure includes a last step for detailing the case of the largest Brazilian oil refinery, REPLAN. This step not only quantifies the water consumption impacts of CO_2 mitigation options, but also identifies whether these impacts could be overcome by the current water supply of REPLAN. In summary, the steps include:

1. To assess the CO_2 mitigation options focusing on the saving potential for the consumption of fuels, steam, electricity and H_2.
2. To estimate the energy and mass balances for a baseline case, including final energy consumption, CO_2 emissions and water requirements. This case does not consider the application of CO_2 emission mitigation options (e.g., fuel switch, fuel saving and carbon capture). This study applies an energy and mass balance simulator – the so-called

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[2] See, for instance, GUEDES (2015).

"CAESAR – Carbon and Energy Strategy for Refineries" tool, which is briefly described here, and better described in the Supplementary Material.

3. To run CAESAR with CO_2 emission prices[3] of 25, 50, 100 and 200 US\$/tCO_2. In this case, the CO_2 emissions mitigation options are selected according to their marginal abatement cost – that is, technological options with costs lower than or equal to the exogenously established CO_2 price are automatically selected by the simulation tool, allowing the construction of a CO_2 average abatement cost curve for all Brazilian oil refineries. The Supplementary Material provides the basic equation associated with the estimation of the abatement cost.

4. To develop a case study for REPLAN, the largest Brazilian refinery in terms of processing capacity, thus quantifying the water stress in detail, or locally. This allows investigating whether mitigation measures that were selected in step 3 can be adopted in cases where a greater water withdrawal is required. This case study is performed using the software tool Water Evaluation and Planning – WEAP (see section 2.2. and Supplementary Material).

2.2. CAESAR tool – Carbon and Energy Strategy Analysis for Refineries

The tool used for evaluating all Brazilian refineries, without detailing the water supply-demand balance at a local level, is the simulator CAESAR – Carbon and Energy Strategy Analysis for Refineries. It was originally developed by TOLMASQUIM and SZKLO (2000), later being used by the Brazilian Government in its Long-Term Energy Plan 2030 (EPE, 2007). Finally, it was updated by GUEDES (2015) and by VÁSQUEZ-ARROYO (2018) and MAGALAR (2018) for incorporating water balances.

The simulation is performed within Excel (visual basic), 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 product output, and refineries' water consumption and withdrawal.

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[3] They represent an established price to be paid for a given amount of CO_2 emitted.

201 Therefore, CAESAR is a bottom-up model mostly based on the simulation of the mass (water,
202 H_2) and energy balances of Brazilian oil refineries. It has an additional feature for optimizing
203 the energy consumption aimed at minimizing the cost of operation of oil refineries. The model
204 also includes a list of CO_2 mitigation options, which are detailed according to the processing
205 units in which they can be implemented, their potential for saving fuel and/or electricity, their
206 investment, operation and maintenance costs, and their penetration rates. In total, 204 options of
207 technologies are available in CAESAR (see Supplementary Material for detailed data).

208 For the carbon price scenarios, CO_2 emission prices were exogenously introduced into the
209 simulator, which also affected the optimization problem that finds the least-cost fuel mix of
210 refineries. Prices of 25, 50, 100 and 200 US\$/tCO_2 were considered, thus building five different
211 scenarios for the current configuration of Brazilian oil refineries. As 204 CO_2 emission
212 mitigation options are available in the simulator, their abatement costs range from negative
213 values, which represent "non-regret" measures, to values above 100 US\$/tCO_2. The highest cost
214 measures would hardly come into effect without economic incentives or more robust
215 technological learning.

216 Therefore, depending on the CO_2 emission price applied, the tool automatically selects different
217 GHG mitigation options from the set list available, affecting the final energy use, CO_2 emissions
218 and water consumption. The Supplementary Material includes the basic data of the model and a
219 description of how to run it.

220

221 2.3. WEAP
222

223 Before using the tool WEAP, REPLAN mass and energy balances were simulated in the above-
224 described tool, CAESAR. This aimed to quantify the impacts of CO_2 emission mitigation
225 options on the water required by REPLAN. Then, the results of water withdrawals obtained in
226 CAESAR were inserted as input into the WEAP tool. This is a tool for integrated water
227 resources management (IWRM) developed by the Stockholm Environmental Institute (SEI).
228 WEAP integrates physical hydrological processes with water withdrawal management and
229 infrastructure, as well as environmental and economic aspects of water planning. Its simulations
230 are based on scenarios that can be analyzed according to different trends in hydrology, water use
231 and demand, demography, technology, operating rules and water management policies
232 (SIEBER and PURKEY, 2015).

233 The WEAP analysis consists of, firstly, configuring the time horizon, catchment areas, system
234 components and configuration of the problem to be evaluated. Then, the model is used to

235   simulate alternative scenarios to assess the impact of different water supply and demand

236   management options, as well as evaluate the water availability within a region of study.

237   The model simulates the use of water in hydrological basins by using a linear programming

238   algorithm, which aims to maximize the water delivered to demand sites, according to a set of

239   priorities defined by the user. When water is limited, the algorithm is formulated to

240   progressively constrain water allocation to the lowest priority demand sites. More details of the

241   model can be found in SIEBER and PURKEY, 2015. See the Supplementary Material for

242   further details on how WEAP is calibrated and used by this study.

243

2.4. Input Data

245

2.4.1. Brazilian Case Study in CAESAR

247

248   The analysis performed by this study was based on the current Brazilian oil refinery system,

249   thus, no greenfield refinery was constructed in the simulation. The mass and energy balances

250   rely on the breakdown in processing units, which have specific characteristics. The capacity of

251   these units is shown in **Table 2**. The average utilization factor of the atmospheric distillation

252   unit was set as 70%, following MME (2018).

253

Table 2 - Brazilian Process Unit Capacities as of December 2017

Unit	Capacity (barrels/d)
ADU	2,138,000
VDU	804,740
FCC	378,729
RFCC	123,158
ALK	6,290
DCU	115,319
CRU	2,386
HDS G	3,054
HDT N	10,528
HDT Q	28,125
HDT D	200,041
HDT I	11,698
LUB	20,009
HGU	126

ADU – atmospheric distillation unit; VDU – vacuum distillation unit; ; FCC – fluid catalytic cracking; RFCC – resid fluid catalytic cracking; ALK – alkylation unit; DCU – delayed coking unit; CRU – catalytic reforming unit; HDS G– gasoline hydrodesulphurization unit; HDT N – naphtha hydrotreatment unit; HDT Q – kerosene hydrotreatment unit; HDT D – diesel hydrotreatment unit; HDT I – severe hydrotreatment unit; LUB – lubricants unit; HGU – hydrogen generation unit (in this case, the capacity is given in MMcfd)

Table 3 shows the estimates for Brazilian refineries' typical utility consumption (negative values mean a net production of the utility by the unit). Although there are variations in the specific energy consumption of utilities for the same unit, depending on the supplier of the technology, local characteristics or even different design considerations, the values adopted in CAESAR seek to represent a typical Brazilian unit.

Table 3 - Process Units' Utilities Specific Energy Consumption

Unit	HP Steam	MP Steam	LP Steam	Electricity	Fuel	Coke	H_2 Consumption	H_2 Production	BFW	CW
	kg/bbl	kg/bbl	kg/bbl	kWh/bbl	MJ/bbl	MJ/bbl	m³/bbl	m³/bbl	m³/bbl	m³/bbl
ADU	0.00	11.00	0.00	0.60	127.00	0.00	0.00	0.00	0.02	0.35
VDU	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.35
FCC	-16.00	20.00	-3.60	8.80	0.00	368.00	0.00	0.00	0.07	1.00
RFCC	-18.00	0.00	0.00	1.00	0.00	368.00	0.00	0.00	0.07	1.00
ALQ	0.00	90.00	0.00	9.00	0.00	0.00	0.00	0.00	0.05	7.00
CRU	-15.60	0.00	0.00	10.00	382.00	0.00	-48.00	0.00	0.02	1.74
DCU	0.00	-18.40	0.00	3.60	126.00	0.00	0.00	0.00	0.06	2.03
HDSG	3.00	0.00	0.00	2.00	105.00	0.00	4.00	0.00	0.04	0.96
HDTN	3.00	0.00	0.00	2.00	105.00	0.00	7.00	0.00	0.01	0.19
HDTQ	4.00	0.00	0.00	3.00	158.00	0.00	7.00	0.00	0.18	0.49
HDTD	4.00	0.00	0.00	3.00	158.00	0.00	7.00	0.00	0.04	0.73
HDTI	5.00	0.00	0.00	6.00	211.00	0.00	17.00	0.00	0.05	0.71
LUB	0.00	1.60	5.60	1.60	135.00	0.00	0.00	0.00	0.05	1.00
HGU	0.00	0.00	0.00	0.00	2.55	0.00	0.00	0.16	0.00	0.00

HP – high pressure; MP – medium pressure; LP – low pressure; BFW – boiler feed water; CW – cooling water

For Brazilian oil refineries, as of 2017, coefficients of water withdrawals per process unit were determined, as indicated in **Table 4**. The coefficients consist of low-pressure steam (LP Steam), medium-pressure steam (MP Steam) and high-pressure steam (HP Steam), related to the process units. The water balance also includes the water consumed in the cooling system (CW – cooling water) and the volume of demineralized water used in the boiler (BFW – boiler feed water) per barrel of oil processed. **Figure 2** shows the basic water balance applied in the simulation tool.

280

281

Table 4 - Water Use Coefficients per Process Unit

	CW (m³/bbl)	BFW (m³/bbl)	LP Steam (kg/bbl)	MP Steam (kg/bbl)	HP Steam (kg/bbl)
ADU	0.3	0.02	-	11.0	-
VDU	0.3	0.05	-	-	-
FCC	1.0	0.07	3.6	20.0	16.0
RFCC	1.0	0.07	-	-	18.0
ALQ	7.0	0.05	-	90.0	-
CRU	1.7	0.02	-	-	15.6
DCU	2.0	0.06	-	18.4	-
HDS G	1.0	0.04	-	-	3.0
HDT N	0.2	0.01	-	-	3.0
HDT Q	0.5	0.18	-	-	4.0
HDT D	0.7	0.04	-	-	4.0
HDT I	0.7	0.05	-	-	5.0
LUB	1.0	0.05	-	-	-
HGU	-	-	-	-	-

282 HP – high pressure; MP – medium pressure; LP – low pressure; BFW – boiler feed water; CW – cooling
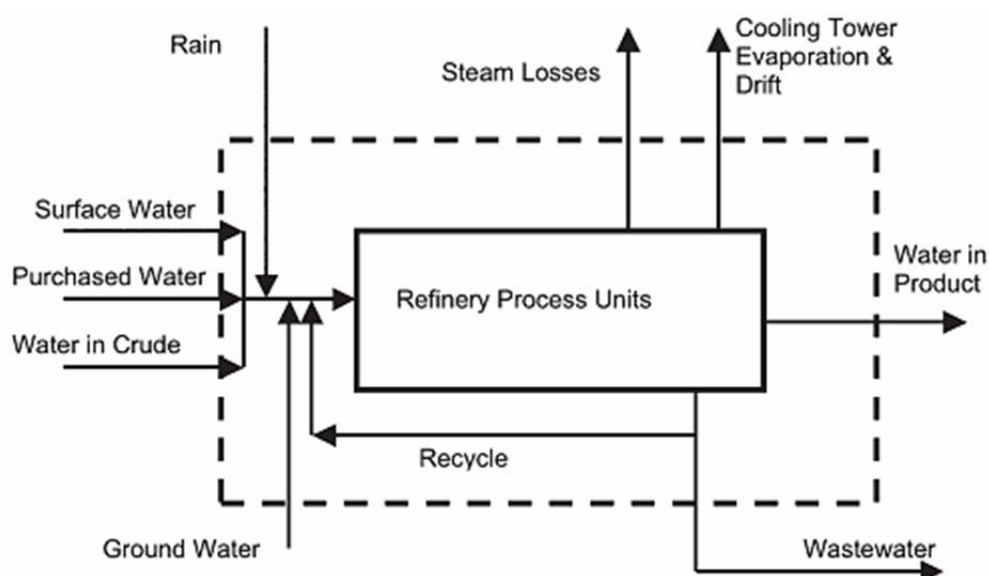283 water

284 Source: VÁSQUEZ ARROYO et al. (2016)

285

287 **Figure 2 - Water balance in CAESAR**

288 Source: Based on IPIECA (2010)

289

290 After obtaining the steam demand, CW and BFW, parameters were adopted to estimate the
291 water consumed by the refinery, based on ANZE (2013). They are composed of the make-up
292 water used in the cooling towers, the make-up water for the boilers and the water used by the
293 processes (water incorporated into products, for instance, in the production of H_2, because of
294 steam reforming and water gas shift, during chemical reactions). A value of 1.7% was
295 considered for the cooling system's total circulating water, according to typical Brazilian oil
296 refineries' concentration ratios (MAGALAR, 2018). For the boiler water make-up, a value of
297 49.7% was applied to the sum of the amount of water used in the boilers (BFW) and the total
298 amount of steam consumed in process units. Steam consumed is defined as lost steam that did
299 not return as condensate. For this, a value of 33% of all generated steam was used (VÁSQUEZ
300 ARROYO et al., 2016). Equation (1) summarizes these assumptions and the water balance.

301

302 $$Demand = (0.017 \times \sum_i CW_i) + \{0.497 \times \sum_i BFW_i + [0.33 \times \sum_i Steam_i]\} \qquad (1)$$

303

304 Where "CW_i" represents the cooling system's circulating water of each process unit "i";
305 "BFW_i" is the amount of water used in boilers of each process unit "i"; "$Steam_i$" is steam
306 consumed in each process unit "i".

307

308 **2.4.2. REPLAN Case Study in WEAP**
309

310 REPLAN is the largest Brazilian refinery in terms of processing capacity (66 thousand m³/day)
311 (ANP, 2018). This refinery is located in Paulínia in the state of São Paulo and is placed in the
312 Piracicaba, Capivari and Jundiaí River Basin (PCJ), which is classified as "critical" in relation
313 to water availability (MAGALAR, 2018).

314 In this study, the water availability of Jaguari basin was calculated by simulating a water
315 balance between the inflows and outflows of its drainage area over time. The Jaguari River
316 basin was chosen due to the catchment point of REPLAN being located in this river. In addition,
317 the basin of the Camanduacaia, Ribeirão do Pinhal rivers was integrated into the case study
318 because these rivers are tributaries of the Jaguari River.

319 The water balance method chosen by this study was the simplified coefficient Method - Rainfall
320 Runoff, in which water requirements are calculated based on evapotranspiration and
321 precipitation data. Twenty-six rainfall stations were evaluated within the three catchment areas:
322 Jaguari River catchment and its tributary rivers, Camanducaia and Pinhal. The data loaded after

323   treatment of the missing data and outliers was the monthly average rainfall. In order to use the

324   mean value of evapotranspiration for each catchment area, the monthly average of all

325   municipalities in each area was calculated. For more details of data, see Supplementary

326   Material.

327   The water outputs considered in this study are the projected demands for public supply,

328   industry, irrigation and for animal husbandry. These demands were identified and projected to

329   the year 2040 to assess the extent to which water availability changes as a function of the

330   multiple uses of water within the PCJ basin and whether the REPLAN could be impacted.

331   The demand for water for urban supply was calculated using a coefficient of water demand per

332   inhabitant per day that was adjusted to account for the water losses in distribution. The same

333   coefficient was used for the projection of water demand for future public supply. The method

334   used for the estimation of the population of each city is described in the Supplementary

335   Material.

336   Water consumption for animal husbandry was calculated from data on the number of animals

337   per city and then calculated the product of the effective number of herds by a per capita

338   coefficient of daily water consumption known as equivalent cattle for water demand. In order to

339   estimate the industrial demand, the volume of water granted by industry in the water agency

340   was consulted.

341   The demand for irrigation is calculated by multiplying the area under cultivation by the

342   difference between the water requirement of the crop and the precipitation occurring over the

343   cultivated area. For this, it is necessary to know the water demand of each crop, which is

344   calculated from the reference evapotranspiration and crop coefficient.

345   After all climatic parameters, data on land use and water demands are inserted into the model,

346   the observed values of the fluviometric stations are compared with the flow data modeled by

347   WEAP. From the observed and simulated flow data, two calibration indices are calculated, the

348   Nash-Sutcliffe efficiency index and the BIAS index.

349   To evaluate the water availability of the REPLAN catchment area, a minimum ecological flow

350   was defined. The minimum flows most commonly used in Brazil are $Q_{7,10}$[4] or Q_{95}[5], depending

351   on the state where the drainage area is located. According to the water resources committee of

352   the PCJ (CBH-PCJ, 2000), areas considered critical are those in which the total water demand

353   exceeds 50% of the minimum availability $Q_{7,10}$. In addition, the water resources policy in the

354   state of Sao Paulo determines that the volume of water withdrawal in the industrial sector

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[4] Lowest flow on seven consecutive days for 10-year return period.
[5] Flow with 95% of permanence over a period.

should be reduced if the flow of the Jaguari River reaches the minimum flow established in specific gauge stations. Therefore, in the water balance simulation done by this study, the analysis tried to find out if periods of restriction of water for REPLAN could happen.

3. Results

3.1. Baseline Scenario for all Brazilian Refineries

The total consumption of utilities and fuels in existing Brazilian refineries is shown in **Table 5**. Negative values indicate exports or utility surpluses, while positive values indicate consumption of utilities.

Table 5 - Utilities Consumption

HP Steam (kt/year)	-752,5
MP Steam (kt/year)	7,340.4
LP Steam (kt/year)	-375.9
Electricity (GWh/year)	12,162.7
Fuel (TJ/year)	284,018.2
Coke (TJ/year)	58,952.6
H$_2$ (M Nm³/year)	6,116.5

HP – high pressure; MP – medium pressure; LP – low pressure

From the utilities consumption, it was possible to determine the fuel consumption. The refinery fuels include natural gas, refinery gas, fuel oil, naphtha and petcoke. Electricity purchased from the grid was also accounted for, either from those refineries that do not have cogeneration or from the excess demand in relation to the capacity of cogeneration units. Natural gas is used for producing hydrogen in HGUs, electricity in cogeneration units, and steam in boilers and direct heating in process units. Refinery gas and fuel oil were accounted for direct heating in process units. In general, leftover refinery gas was directed toward flare emissions accounting. Furthermore, a 100% flare combustion efficiency was assumed to be conservative on the GHG emission estimates. Finally, the consumption of petcoke was accounted for in FCC and RFCC units. **Table 6** shows the estimation of the final energy consumption for the existing Brazilian refineries.

Table 6 - Final Energy Consumption - *Baseline* (PJ/year)

Natural Gas	367.8

Refinery Gas	84.4
Fuel oil	85.4
Coke	59.0
TOTAL	596.6
Grid Eletricity (GWh/year)	7,252.7

382

383   As such, the water requirement of the existing Brazilian refineries is detailed in **Table 7**. The

384   water intensity of 108.2 m³/bbl is compatible with the figures found in VANELLI (2004) for

385   REVAP – Refinaria Henrique Lage; PETROBRAS (2005) and NOGUEIRA (2007) for

386   REPLAN – Refinaria de Paulínia; SCHOR (2006) for REDUC – Refinaria Duque de Caixas;

387   and CETESB (2011) for RPBC – Refinaria Presidente Bernardes.

388

389   **Table 7 - Water Requirements - Baseline**

BFW (t/h)	8,809.2
CW (t/h)	118,486.2
Steam (t/h)	3,720.4
Condensed Steam (t/h)	2,492.7
BFW spent (t/h)	10,036.9
BFW Make-up (%)	49.7
BFW Make-up (t/h)	4,988.4
CW Make-up (%)	1.7
CW Make-up (t/h)	2,014.3
Consumption (t/h)	1,610.5
Withdrawal (t/h)	7,002.6
Consumption (m³/bbl)	24.9
Withdrawal (m³/bbl)	108.2
Consumption (km³/year)	14107.9
Withdrawal (km³/year)	61351.7

390   BFW – Boiler feed water; CW – Cooling water

391

392   It was also possible to estimate the CO_2 emissions of Brazilian refineries as of 2017, through the

393   multiplication of the emission factors reported by IPCC (2006) of the respective fuels used by

394   Brazilian refineries (**Table 8**). For electricity's CO_2 emissions, the average Brazilian grid

395   emission factor for 2017 was considered, equal to 92.7 tCO_2/GWh (MCTIC, 2018).

396

397   **Table 8 - CO_2 Emissions ($MtCO_2$/year) - Baseline**

Natural Gas	20.6
Refinery Gas	4.9
Fuel Oil	6.6
Coke	5.7
Grid Electricity	0.4

TOTAL	38.2

398

399 By dividing the total emissions by the processed feed, this study estimated an emission intensity
400 of 0.4 tCO_2/t oil, which is compatible with the 2012 data presented by the Brazilian oil company
401 that owns most of the country's refineries (PETROBRAS, 2013)[6]. Just for comparison,
402 worldwide several works in the literature present CO_2 emission intensities of oil refineries
403 hovering between 0.1 and 0.4 tCO_2/t of oil processed, with an average of 0.22 (CONCAWE,
404 2008; IEAGHG, 2008; STRAELEN et al., 2010; DNV, 2010). For example, the US has an
405 average emission of 0.33 tCO2/t of processed oil, while the European Union has an average
406 value of 0.27 (EPA, 2014).

407 Finally, concerning the relationship between CO_2 emissions and water withdrawals, the
408 estimative for the baseline scenario is 0.62 tCO_2/m³. **Figure 3** and **Figure 4** present, for this
409 scenario, the most representative units in terms of water consumption and CO_2 emissions,
410 respectively.
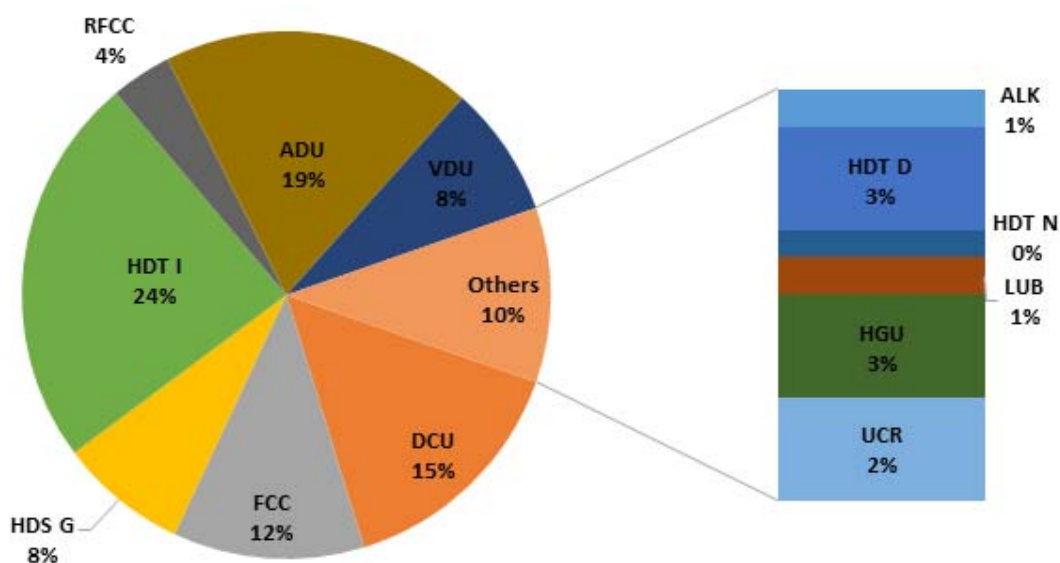
411

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[6] Equal to 0.45 tCO_2/ t of oil processed in 2012. Of course, this intensity may vary slightly among years given the focus of the ADU campaign (in our study we focused on diesel), the possible maintenance of downstream units, which can affect the utilization factor of oil refineries (we used the ADU average utilization factor of 2017, equal to 70%), and the crudes processed in the refineries. In our study, we have considered the ramp-up of a lighter and sweeter feed that has been made available in Brazil in the last five years, from pre-salt fields. That is why we run the model with 4% of the feed from paraffinic oils from Saudi Arabia; 2% from ultra-light African crudes; 32% from Brazilian heavy crudes, and the remaining 62% from medium-to-slightly light Brazilian crudes, mostly from pre-salt fields. Therefore, the feedstock blend has become lighter than it was in 2012.
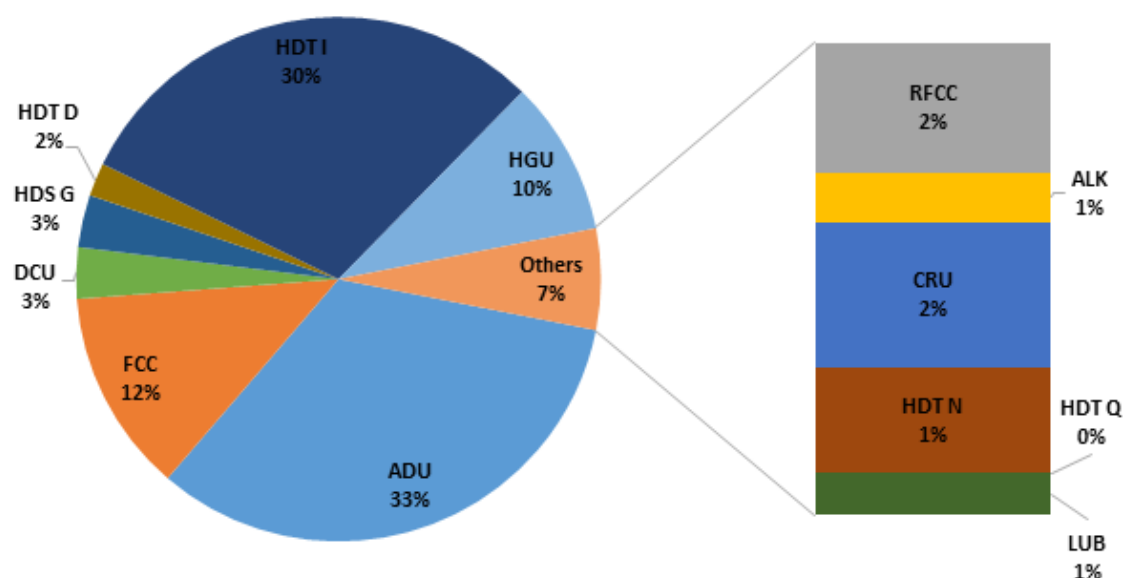
Figure 3 - Water consumption per processing unit in the baseline scenario

ADU – atmospheric distillation unit; VDU – vacuum distillation unit; ; FCC – fluid catalytic cracking; RFCC – resid fluid catalytic cracking; ALK – alkylation unit; DCU – delayed coking unit; CRU – catalytic reforming unit; HDS G – gasoline hydrodesulphurization unit; HDT N – naphtha hydrotreatment unit; HDT Q – kerosene hydrotreatment unit; HDT D – diesel hydrotreatment unit; HDT I – severe hydrotreatment unit; LUB – lubricants unit; HGU – hydrogen generation unit

Figure 4 - CO$_2$ emissions per processing unit in the baseline scenario

ADU – atmospheric distillation unit; VDU – vacuum distillation unit; ; FCC – fluid catalytic cracking; RFCC – resid fluid catalytic cracking; ALK – alkylation unit; DCU – delayed coking unit; CRU – catalytic reforming unit; HDS G – gasoline hydrodesulphurization unit; HDT N – naphtha hydrotreatment unit; HDT Q – kerosene hydrotreatment unit; HDT D – diesel hydrotreatment unit; HDT I – severe hydrotreatment unit; LUB – lubricants unit; HGU – hydrogen generation unit

According to SZKLO and SCHAEFFER (2007), most CO$_2$ emissions from Brazilian refineries come from burning fuels. Interestingly, the fuel consumption of refineries in absolute terms concentrates on few processes, which are not the most energy intensive (in terms of energy consumption per barrel) but process large volumes of feedstock. Typically, atmospheric and vacuum distillation units account for 35-40% of a refinery's final energy use (API, 2000) because any barrel of oil entering a refinery passes through the topping separation units. This explains their share of CO$_2$ emissions. Also, for global refining, between 16% and 20% of the total are non-energy emissions associated with the chemical reactions of hydrogen production and cracking of the FCC (SZKLO AND SCHAEFFER, 2007). This average figure agrees with our findings for Brazil. Finally, severe hydrotreatment (for unstable and unfinished distillates) results in both higher water consumption and CO$_2$ emissions due to the severity (temperature

437   higher than 450°C, H_2 partial pressure up to 21 MPa, and low liquid hourly space velocity[7] and

438   hydrogen pressure) under which reactions must happen (GARY et al, 2007; STANISLAU et al,

439   2010).

440

3.2. CO_2 Price Scenarios for all Brazilian Refineries

441

442

443   As described above, four CO_2 price scenarios were simulated in CAESAR. According to the

444   levelized cost of mitigation options on the database of the tool, different options were selected

445   for each scenario. Moreover, the fuel mix also changed to minimize operational costs

446   considering the CO_2 prices (and the emission factors of each possible fuel to be used). **Table 9**

447   summarizes the results for different CO_2 prices, and **Figure 5** shows CO_2 emissions and water

448   requirements for different CO_2 emission prices scenarios.

449

Table 9 – Summary of Results

Final Energy Use (PJ/year)	CO_2 Emission Price (US$/t$CO_2$)				
	Baseline	**25**	**50**	**100**	**200**
Natural Gas	367.84	367.84	367.84	367.84	367.84
Refinery Gas	84.39	84.39	84.39	84.39	84.39
Fuel oil	85.26	78.76	78.22	71.32	62.05
Coke	58.95	58.95	58.95	58.95	58.95
TOTAL	596.40	589.94	589.40	582.50	573.23
Grid Eletricity (GWh/year)	7252.71	7393.02	7199.61	7772.97	7643.62
Water requirements					
Consumption (km³/year)	14107.86	14143.04	14143.04	14154.36	14154.36
Withdrawal (km³/year)	61351.69	62191.48	62191.48	62228.12	62228.12
CO_2 emissions (MtCO_2/year)	38.20	34.43	34.38	28.18	27.46

450

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[7] This is expressed in m^3 of fresh feed per m^3 of catalyst per hour. The inverse of LHSV is generally called residence time (STANISLAU et al, 2010).
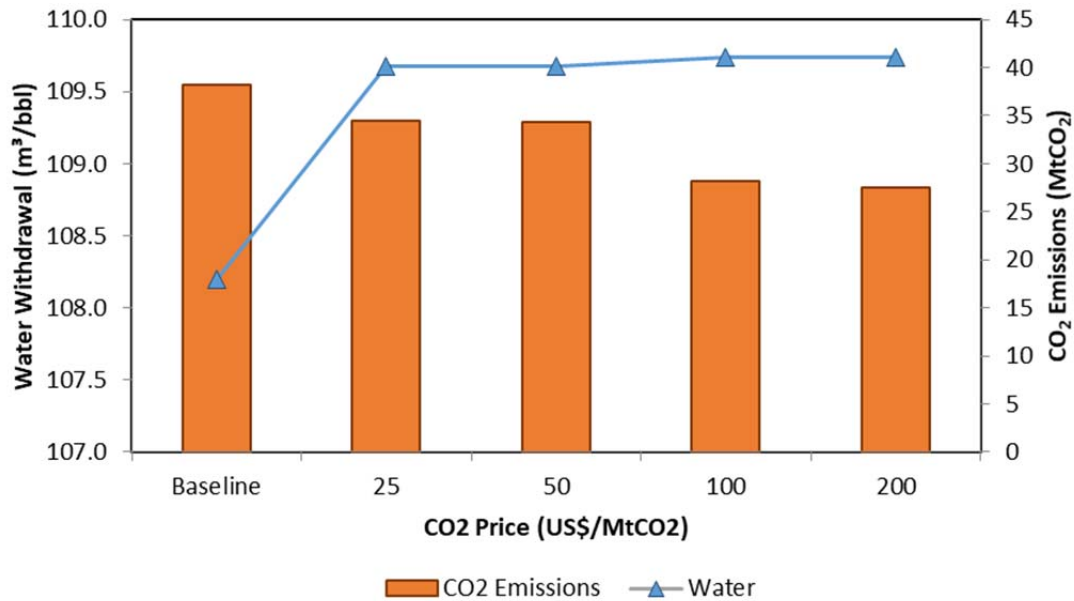
Figure 5 - Water withdrawal *versus* CO₂ emissions

The most significant CO_2 emission abatement occurs at 25 and 100 US\$/tCO_2, 10% and 26%, respectively, compared to the baseline. This is explained by the total abatement potential of the technologies found in the cost ranges 0-25 US\$/tCO_2 and 50-100 US\$/tCO_2, equal to 143.5 and 205.7 MtCO_2 (see Supplementary Material). In respect to water requirements, a slight change of less than 1% occurs between the baseline scenario and 25 US\$/tCO_2 scenario. In other scenarios, the water withdrawals remain practically stable, with a small change, less than 0.5% in the 100US\$/tCO_2 scenario. To better illustrate the relationship between the abatement costs and the accumulated abatement potential, the abatement cost curve (**Figure 6**) was produced, including the 204 technologies considered in the study.
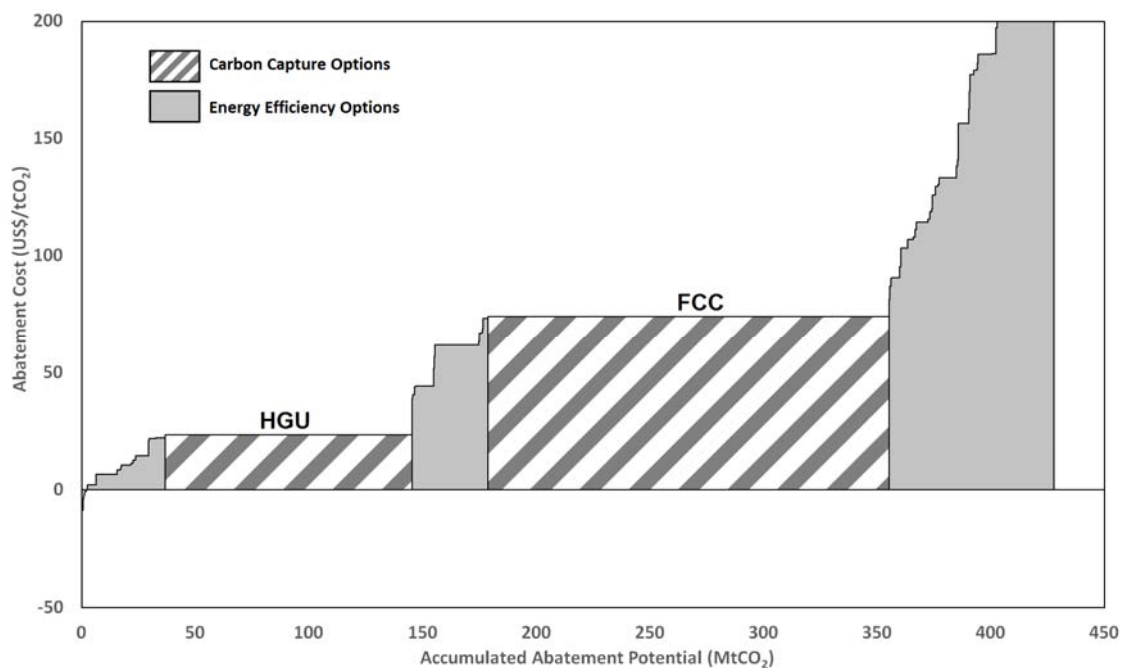
Figure 6 - Abatement cost curve for Brazilian refineries
Note: HGU – Hydrogen generation unit; FCC – Fluidized catalytic cracking.

The graph performs a static analysis of the accumulated abatement potential of the mitigation options. For instance, it demonstrates that at a cost of $200/tCO$_2$, it would be possible to implement a series of measures that have a cumulative abatement potential of 423.78 MtCO$_2$. The two striped areas marked on the graph represent the CC technologies, while the gray-colored areas represent the other mitigation options. The first one, with an accumulated abatement potential of 145.5 MtCO$_2$, refers to the HGU capture with SMR/MDEA, while the second one, with 355.3 MtCO$_2$ of accumulated abatement potential, represents the FCC capture with Oxyfiring. These carbon capture technologies represent 65.7% of the total accumulated abatement cost, given the cracking pattern of Brazilian refineries and the recent regulations that tightened diesel and gasoline specifications in the country.

In the end, the findings of this study show that the co-benefits of GHG abatement measures that also reduce steam consumption (e.g., reduction of heat storage between ADU and VDU, steam fouling reduction in ADU, installation of vacuum pumps to replace steam injectors in ADU, increase AGR solvent concentration in HDS G, replace steam drive for electric in HDT N, and installation of CO-kiln in regenerative tower HRSG in FCC), which were chosen[8] by our

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[8] Steam fouling reduction in ADU and vacuum pumps to replace steam injectors in ADU are installed at 25 US$/tCO$_2$. Increase AGR solvent concentration in HDS G is chosen at 50 US$/tCO$_2$. Replace steam drive for electric in HDT N is chosen at 100 US$/tCO$_2$. CO-kiln in regenerative tower HRSG in FCC is installed at 200 US$/tCO$_2$ tax.

482   simulations, were offset by the water consumption increase related to CC options, especially in

483   HGU. In summary, at a national level and on average, CO_2 mitigation impacts on water use by

484   oil refineries in Brazil are neutral. **Figure 7** illustrates how steam consumption reduction from

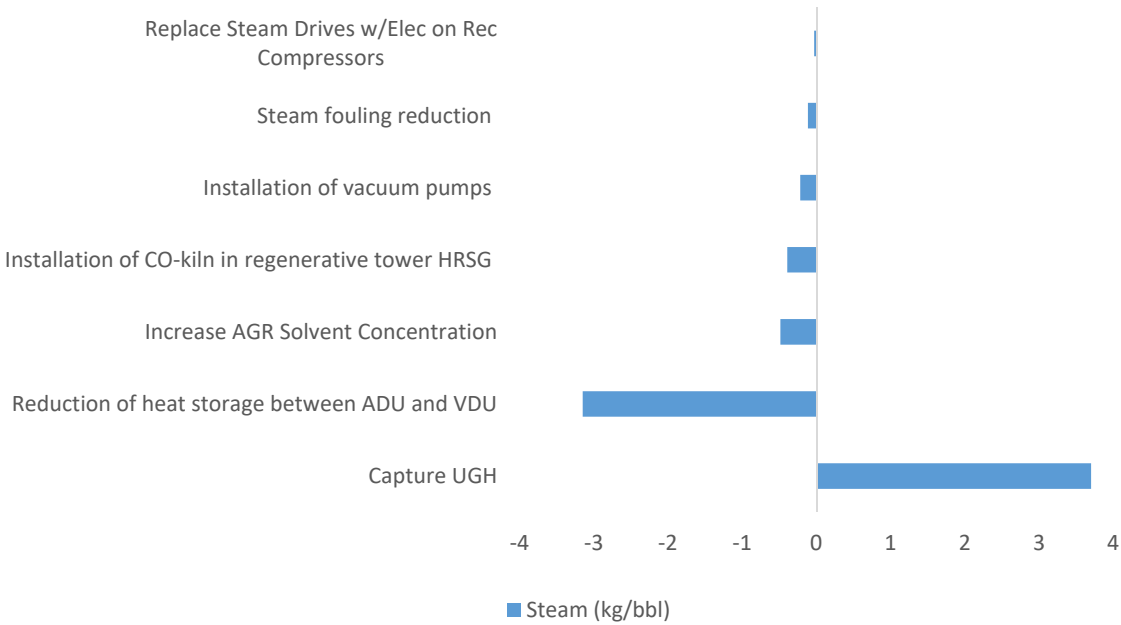485   some mitigation measures is overcome by the increase required with CC implementation.

486

487   **Figure 7 – Steam requirements impacts of CO_2 mitigation options**

488

3.3.   Case Study: REPLAN

490

491   At a local level, for the largest Brazilian oil refinery, the water balance undertaken showed that,

492   although there was no unmet water demand at the REPLAN's catchment point, the conflict

493   between the multiple water users in the basin should intensify. This is due to the trend in the

494   river flow being progressively closer to the critical threshold of 50% of the minimum

495   availability ($Q_{7,10}$). In addition, it was observed that the point of flow observation at Jaguari

496   River faces instants when the flow must be restricted. This means that REPLAN may sometimes

497   suffer impacts on its operation due to a 30% reduction in the volume of water it receives from
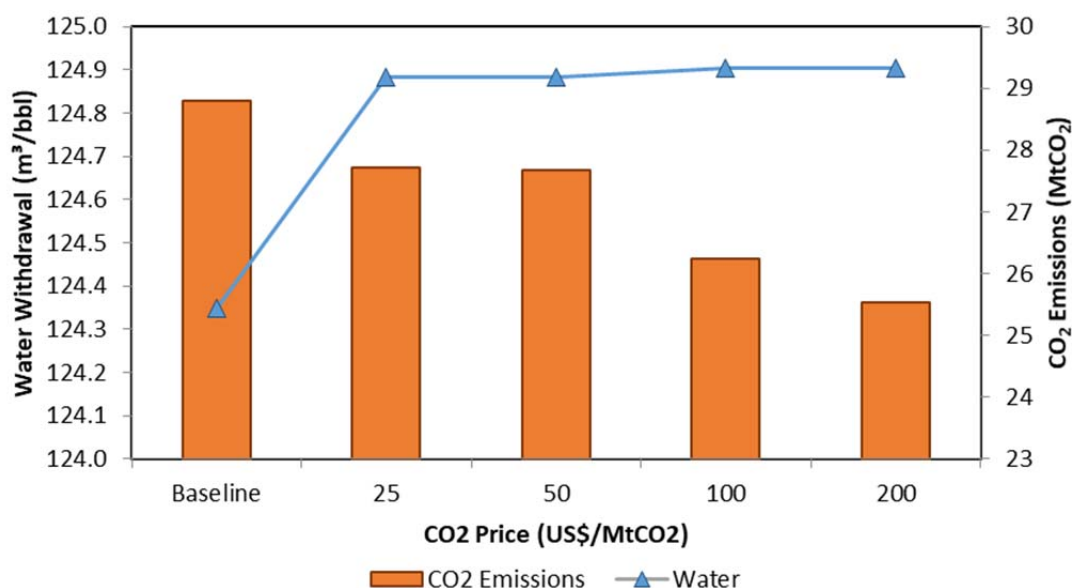
498   the Jaguari River.

Figure 8 - Water withdrawal versus CO_2 abatement in REPLAN

Figure 8 shows an increase in water withdrawal in all scenarios. Although some mitigation measures reduce steam consumption, in the refinery's overall water balance, this reduction is offset by the increase in the demand for boiler feed water and for cooling. Mitigation measures costing up to US$ 25/MtCO$_2$ were the ones that most demanded water due to the increase in boiler feed water need, which was 1.4% more than in the baseline scenario. In addition, the slight increase that occurred between scenarios US$ 50/MtCO$_2$ and 100 was due to the implementation of CC, which increased the demand for cooling water.

Nevertheless, as a final balance, a reduction of less than 1% was obtained when implementing all CO_2 mitigation measures in REPLAN. This means that, contrary to what happens in other energy sectors (ZHAI and RUBIN, 2011; MERSCHMANN et al., 2012), the implementation of CO_2 abatement in oil refineries has no significant impact on water consumption (no negative trade-off). However, this also means that the water stress in oil refineries should be dealt with measures not directly linked to CO_2 abatement (no significant co-benefits). This is valid both at local and country levels.

4. Final Remarks

This study developed an energy, CO_2, H_2, water balance simulator for Brazilian oil refineries, and applied it to different scenarios of CO_2 mitigation (at 25, 50, 100 and 200 US$/tCO$_2$) aiming at investigating the climate-energy-water nexus. A Baseline scenario, i.e., a scenario

522 without CO_2 prices was also elaborated. Results for both scenarios included final energy
523 consumption, CO_2 emissions and water requirements. The most significant reductions in CO_2
524 emissions were due to the implementation of the carbon capture. However, this option offsets
525 the co-benefits of CO_2 abatement measures that reduced the water requirements of Brazilian oil
526 refineries, especially those already located in areas under water supply stress, such as the largest
527 refinery in Brazil (REPLAN), whose water balance with carbon mitigation options was detailed
528 in this study.

529 Nevertheless, as this study focused on the impacts of CO_2 mitigation options on water
530 requirements, it was not able to follow the reverse path of the nexus: from climate to water
531 availability. This means that climate change can affect the water availability to oil refineries
532 (water supply, instead of water demand side). Hence, future studies could focus on this issue,
533 also including the analysis of alternatives to regularize river flows to deal with climate impacts
534 on water supply. Another idea could be optimizing refineries for minimizing water consumption
535 (or withdrawals).

536 It is also worth noting that this study tried to validate the findings of the tools used by
537 comparing them to real data from Brazil. However, an important issue for the simulation tool is
538 to calibrate the feedstock blend to be run, and the focus of the refinery operation. As of today,
539 although the Brazilian refinery system, on average, focuses on diesel optimization (e.g. when
540 establishing the distillation cuts), single refineries can present a different feature (e.g. focusing
541 on lube oils or petrochemicals). Similarly, the yearly focus of the average refinery operation on
542 diesel does not mean that this is valid for all days of the year.

543 Finally, although the 204 CO_2 mitigation options considered by this study represent an extensive
544 list of measures, there are always new possibilities to be assessed. For example, some studies
545 have evaluated the use of renewable energy sources to supply the energy demand (PINSKE et
546 al., 2012) and the hydrogen consumption (SILVA, 2017) of oil refineries.

547

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References

ANA, 2017. Conjuntura dos Recursos Hídricos no Brasil. Regiões Hidrográficas. Brasília: Agência Nacional de Águas. Available at: http://www.snirh.gov.br/portal/snirh/centrais-de-conteudos/conjuntura-dos-recursos-hidricos/conj2017_rel_ingles-1.pdf (accessed 05.08.18).

ANP, 2018. Anuário Estatístico Brasileiro do Petróleo, Gás Natural e Biocombustíveis 2018. Agência Nacional do Petróleo, Gás Natural e Biocombustíveis. Available at: http://www.anp.gov.br/publicacoes/anuario-estatistico/anuario-estatistico-2018#Se%C3%A7%C3%A3o%202 (accessed 10.07.18).

ANZE, M., 2013. Otimização Do Uso De Água Em Refinarias De Petróleo. 160 p. – Universidade de São Paulo, Brazil.

API – American Petroleum Institute, 2000. Technological Roadmap. Houston: API, 2000

BARAJAS, J., ROMAN, R., SOTELO, D., 2006. Multiplicity of steady states in FCC units: effect of operating conditions. Fuel (85), 849-859.

BARROS, M.M., SZKLO, A., 2015. Petroleum refining flexibility and cost to address the risk of ethanol supply disruptions: The case of Brazil. Renewable Energy (77), 20-31.

BERGH, C., 2012. Energy Efficiency in the South African Crude Oil Refining Industry: Drivers, Barriers and Opportunities. Dissertação de Mestrado, Programa de Engenharia de Energia Sustentável, Universidade de Cape Town, África do Sul.

CASTELO BRANCO, D., SZKLO, A., SCHAEFFER, R., 2010. CO_2 emissions abatement costs of reducing natural gas flaring in Brazil by investing in offshore GTL plants producing premium diesel. Energy (35), 158-167.

CASTELO BRANCO, D.A., SZKLO, A., GOMES, G., BORBA, B.S.M.C., SCHAEFFER, R., 2011. Abatement costs of CO_2 emissions in the Brazilian oil refining sector. Applied Energy (11), 3782-3790.

CETESB, 2011. Licenciamento Ambiental Prévio de ampliação da Refinaria RPBC do empreendimento Carteira de Diesel, São Paulo. Available at: http://arquivos.ambiente.sp.gov.br/consema/2011/11/oficio_consema_2011_017/Parecer_Tecnico_CETESB_4055_11_TA_sobre_o_EIA-RIMA_da_Carteira_de_Diesel_da_RPBC.pdf (accessed 20.08.2018).

CHAN, W. N., 2006. Quantificação e redução de emissões de gases de efeito estufa em uma refinaria de petróleo. Master Thesis, Universidade Estadual de Campinas.

COELHO, J. M. F., SZKLO, A., 2015. Dealing with petroleum surpluses in Brazil through optimization refining model. Energy Strategy Reviews (6), 80-91.

CONCAWE, 2000. Carbon, Sulphur and hydrogen in oil refineries. Review, Volume 9, Number 1.

CONCAWE, 2008. Impact of product quality and demand evolution on EU refineries at the 2020 horizon CO_2 emissions trend and mitigation options. Report 8/08, Belgium.

CONCAWE, 2012. Refinery energy systems and efficiency. Review, Volume 21, Number 1.

SILVA, G. N., 2017. Produção de hidrogênio renovável via Power to gas para mitigação de emissões de CO_2 do refino do petróleo e maior aproveitamento da energia eólica. Dissertação de Mestrado. Rio de Janeiro: UFRJ/ COPPE/ Programa de Planejamento Energético.

DNV, 2010. Global Technology Roadmap for CCS in Industry - Sectoral Assessment: Refineries. Det Norske Veritas, Research Report for UNIDO, London, United Kingdom.

EPA, 2010. Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Petroleum Refining Industry. United Stated Environmental Protection Agency.

597 EPA, 2014. Greenhouse Gas Inventory Data Explorer. United Stated Environmental Protection Agency.
598 Available at: www.epa.gov.br (accessed 19.07.18).

599 EPE, 2007. Plano Nacional de Energia 2030 / Ministério de Minas e Energia, colaboração Empresa de
600 Pesquisa Energética. Brasília, Brazil. Available at: http://www.epe.gov.br/sites-pt/publicacoes-dados-
601 abertos/publicacoes/PublicacoesArquivos/publicacao-165/topico-173/PNE%202030%20-
602 %20Proje%C3%A7%C3%B5es.pdf (accessed 30.08.18).

603 GARCÍA, A. A. C, 2015. Challenge of the integration of CO2 capture in the refining sector. Club Español
604 de La Energía/ World Petroleum Council – Comitê Español.

605 GARY, J., H., HANDWERK, G. E., 2001. Petroleum Refining: Technology and Economics. 4th edition.
606 New York, United States.

607 Gary, J.H., Handwerk, G.E. and Kaiser, M.J., 2007. Petroleum Refining: Technology and Economics. 5th
608 edition, CRC Press, Boca Raton.

609 GOMES, G. L., SZKLO, A., SCHAEFFER, R., 2009. The impact of CO2 taxation on the configuration
610 of new refineries: An application to Brazil. Energy Policy (37), 5519-5529.

611 GUEDES, F. P. D. C., 2015. Avaliação de alternativas para redução do uso final de energia no setor de
612 refino de petróleo brasileiro e estimativa de custos de abatimento de emissões de gases de efeito estufa.
613 Dissertação de Mestrado. Rio de Janeiro: UFRJ/COPPE/ Programa de Planejamento Energético.

614 HALLACK, L. N., SZKLO, A. S, PEREIRA JÚNIOR, A. O., SCHMIDT, J., 2017. Curve-fitting
615 variants to model Brazil's crude oil offshore post-salt production. Journal of Petroleum Science and
616 Engineering (159), 230-243.

617 HIGHTOWER, M., PIERCE, S. A., 2008. The energy challenge. Nature (452), 285-286.

618 HWANG, S., MOORE, I., 2011. Water network synthesis in refinery. Korean Journal of Chemical
619 Engineering 28:1975.

620 HYDROCARBON PROCESSING, 2008. Refining Processes Handbook. CD-ROM, Gulf Publishing
621 Company, EUA.

622 IEA, 2016. World Energy Outlook 2016. International Energy Agency, Paris, France.

623 IEA GHG, 2008. Carbon Dioxide Capture and Storage in the Clean Development Mechanism: Assessing
624 market effects of inclusion. IEA Greenhouse Gas R&D Programme, Cheltenham.

625 IPCC, 2006. Guidelines for National Greenhouse Gas Inventories. National Greenhouse Gas Inventories
626 Programme, Hayama, Japão.

627 IPIECA, 2010. Petroleum Refining Water/Wastewater Use and Management. [s.l.]: [s.n.], 2010.
628 Available at: http://www.perf.org/images/Archive_Refining_Water.pdf (accessed 02.08.18).

629 JOHANSSON, D., ROOTZÉN, J., BERNTSSON, T., JOHNSOON, F., 2012. Assessment of strategies
630 for CO2 abatement in the European petroleum refining industry. Energy (42), 375-386.

631 MAGALAR, L., 2018. Análise da disponibilidade hídrica como um fator de restrição à produção de
632 derivados em refinarias. Rio de Janeiro: UFRJ/COPPE/ Programa de Planejamento Energético.

633 MAGNESCHI, G., ZHANG, T., MUNSON, R., 2017. The impact of CO2 capture on water requirements
634 of power plants. Energy Procedia (114), 6337 – 6347.

635 MCTI, 2013. Annual Estimates of Greenhouse Gas Emissions in Brazil (Estimativas anuais de emissões
636 de gases de efeito estufa no Brasil). Brasília, Brasil.

637 MCTIC, 2018. Método da análise de despacho - Fatores de Emissão de CO2 pela geração de energia
638 elétrica no Sistema Interligado Nacional do Brasil - Ano Base 2017. Ministério da Ciência, Tecnologia,
639 Inovações e Comunicações. Available at:

640 http://www.mctic.gov.br/mctic/opencms/ciencia/SEPED/clima/textogeral/emissao_despacho.html
641 (accessed 15.08.18).

642 MERSCHMANN, P. R. C., VASQUEZ, E., SZKLO, A. S., SCHAEFFER, R., 2012. Modeling water use
643 demands for thermoelectric power plants with CCS in selected Brazilian water basins. International
644 Journal of Greenhouse Gas Control (13), 87–101.

645 MEYERS, R. A., 2004. Handbook of Petroleum Refining Processes. 3rd edition. McGraw-Hill
646 Handbooks.

647 MME, 2018. Relatório do Mercado de Derivados de Petróleo. Número 148. Ministério de Minas e
648 Energia/ Secretaria de Petróleo, Gás Natural e Biocombustíveis/ Departamento de Combustíveis
649 Derivados de Petróleo.

650 MORROW III, W., MARANO, J., SATHAVE, J., HASANBEIGI, A., Xu, T., 2013. Efficiency
651 Improvement in the United States Petroleum Refining Industry. Environmental Energy Technologies
652 Division, California.

653 MUGHEES, W., AL-AHMAD, M., 2014. Application of Water Pinch Technology in Minimization of
654 Water Consumption at a Refinery. Computers & Chemical Engineering (73), 34-42.

655 NOGUEIRA, D.M., 2007. Balanço Hídrico na Refinaria de Paulínia e Alternativas para Reuso de Água:
656 Construção de uma Ferramenta Auxiliar para o Gerenciamento dos Recursos Hídricos. Universidade
657 Estadual de Campinas.

658 OIL and GAS JOURNAL, 2018. 2018 World Wide Refining Survey.

659 PAN, L., LIU, P., MA, L., LI, Z., 2012. A supply chain based assessment of water issues in the coal
660 industry in China. Energy Policy (48), 93-102.

661 PETROBRAS, 2005. Estudo de Impacto Ambiental da Refinaria De Paulínia.

662 PETROBRAS, 2013. Relatório de Sustentabilidade 2013. Disponível em:
663 http://www.investidorpetrobras.com.br/pt/governanca/relatorio-de-sustentabilidade/relatorio-de-
664 sustentabilidade-2013.htm (accessed 30.07.2018)

665 PETROBRAS, 2016. Relatório de Sustentabilidade 2015. Available at:
666 www.investidorpetrobras.com.br/download/4512 (accessed 11.07.18).

667 PINKSE, J., VAN DEN BUUSE, D., 2012. The development and commercialization of solar PV
668 technology in the oil industry. Energy Policy (40), 11–20.

669 ROCHEDO, P. R. R.; SZKLO, A. S., 2013. Economic analysis under uncertainty of coal fired capture-
670 ready power plants. International Journal of Greenhouse Gas Control, v. 12, p. 44-55.
671 https://doi.org/10.1016/j.ijggc.2012.10.005

672 ROCHEDO, P. R. R., COSTA, I. V. L., IMPÉRIO, M., HOFFMANN, B. S., MERSCHMANN, P. R. C.,
673 OLIVEIRA, C. C. N., SZKLO, A., SCHAEFFER, R., 2016. Carbon capture potential and costs in Brazil.
674 Journal of Cleaner Production (131), 280-295.

675 SCHOR, A.R., 2006. Riscos e alternativas para o abastecimento de água em uma refinaria de petróleo
676 estudo de caso: refinaria duque de caxias - reduc. Universidade Federal do Rio de Janeiro.

677 SIEBER, J.; PURKEY, D., 2015. Water Evaluation And Planning System User Guide. [s.l: s.n.].
678 Available at: http://www.weap21.org/downloads/WEAP_User_Guide.pdf (accessed 05.01.16).

679 STANISLAUS, A.; MARAFI, A.; RANA, M. S., 2010. Recent advances in the science and technology of
680 ultra-low sulfur diesel (ULSD) production. Catalysis Today, [s.l.], v. 153, no 1–2, p. 1–68, 2010. ISBN:
681 09205861, ISSN: 09205861, DOI: 10.1016/j.cattod.2010.05.011.

682 STRAELEN, J.; GUEZEBROEK, F.; GOODCHILD, N.; PROTOPAPAS, G.; MAHONY, L., 2010.
683 International Journal of Greenhouse Gas Control (4), 316–320.

684   SUN, P., ELGOWAINYA, A., WANGA, M., HANA, J., HENDERSON, R., 2018. Estimation of U.S.
685   refinery water consumption and allocation to refinery products. Fuel (221), 542-557.

686   SZKLO, A. S.; ULLER, V. C.; BONFÁ, M. H. P., 2012. Fundamentos do Refino do Petróleo. Tecnologia
687   e Economia. 3a Edição ed. Rio de Janeiro: Editora Interciência, 2012. 344 p.

688   SZKLO, A., SCHAEFFER, R., 2007. Fuel specification, energy consumption and CO2 emission in oil
689   refineries. Energy 32 (7), 1075-1092.

690   TOLMASQUIM, M. T.; SZKLO, A. S., 2000. Matriz Brasileira na Virada do Milênio. Rio de Janeiro:
691   COPPE/ UFRJ.

692   UNITED NATIONS, 2010. Carbon Capture and Storage in Industrial Applications: Technology
693   Synthesis Report. Working Paper, Vienna.

694   UNITED NATIONS, 2015. Transforming Our World: The 2030 Agenda for Sustainable Development.
695   Available   at: https://sustainabledevelopment.un.org/post2015/transformingourworld/publication
696   (accessed 15.08.2018)

697   UNITED NATIONS, 2016. Sustainable Development Goals. Available in :
698   http://www.undp.org/content/undp/en/home/sustainable-development-goals.html (accessed 15.08.2018)

699   VANELLI, C.A., 2004. Conservação De Água Em Refinaria De Petróleo: O Caso Da Revap. Dissertação
700   de Mestrado. Programa de Pós-Graduação da Universidade Federal de Itajubá.

701   VÁSQUEZ ARROYO, E. M., 2018. Incorporação do nexo energia-água em um modelo de otimização da
702   expansão do sistema energético brasileiro. Rio de Janeiro: UFRJ/COPPE/ Programa de Planejamento
703   Energético.

704   VÁSQUEZ ARROYO, E. M., et al., 2016. A DISPONIBILIDADE HÍDRICA COMO POSSÍVEL
705   RESTRIÇÃO AMBIENTAL PARA A PRODUÇÃO DE DERIVADOS DE PETRÓLEO NO BRASIL.
706   In: Rio Oil & Gas. [s.l.]: [s.n.].

707   WU, M., CHIU, Y., 2011. Consumptive water use in the production of ethanol and petroleum gasoline.
708   ANL/ESD/09-1, Argonne National Laboratory.

709   WORRELL, E.; GALITSKY, C., 2005. Energy Efficiency Improvement and Cost Saving Opportunities
710   for Petroleum Refineries. Environmental Energy Technologies Division, Ernest Orlando Lawrence
711   Berkeley National Laboratory, Califórnia, EUA.

712   WORRELL, E; GALITSKY, C., 2003. Profile of the Petroleum Refining Industry in California Industries
713   of the Future Program. Environmental Energy Technologies Division, Ernest Orlando Lawrence Berkeley
714   National Laboratory, Califórnia, EUA.

715   ZHAI, H., RUBIN, E. S., 2011. Carbon capture effects on water use at pulverized coal power plants.
716   Energy Procedia (4), 2238-2244.