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## ORION – OIL AND RENEWABLES REFINING INDUSTRY OPTIMIZATION AND SYNERGIES

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# ORION - Oil and renewables Refining Industry Optimization and syNergies

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## Abstract

This paper introduces ORION, a GAMS-based Mixed Integer Linear Programming model designed to optimize the refining sector. ORION is a multiplant model and considers the spatial distribution of supply, demand, and process units. It addresses not only conventional refinery operations, but also focuses on novel opportunities for integrating the sector into a context of carbon intensity reduction: processing of both fossil and renewable feedstocks, and the construction of small-scale modular refineries. Moreover, the model allows a two-step optimization to identify refineries with low utilization factors and subsequently evaluate how the industry responds to their closure. Those features of the model are demonstrated in a case study for Brazil, illustrating that ORION is useful for assessing risks (e.g., stranded assets) and opportunities (e.g., biomass co-processing, small-scale refineries) in decarbonization scenarios.

## 1. Introduction

This work presents ORION (*Oil and renewables Refining Industry Optimization and syNergies*), an optimization model for analyzing the refining sector and is the result of a partnership between IFP School - IFPEN, in France, and the Federal University of Rio de Janeiro (UFRJ), in Brazil[1]. The theme is of interest for France and Brazil since both countries

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[1] The development of the model started during the PhD visiting research of Fernanda Pires Domingues Cardoso Guedes at the IFP School and continued during the PhD visiting research of Clarissa Bergman-Fonte at the same institution. The research was under the supervision of Professor Frédéric Lantz, from IFP School and of Professors Alexandre Szklo and Pedro Rochedo, from UFRJ.

have a consolidated oil refining industry [1], [2], and it is crucial to understand the possibilities for the evolution and integration of this sector to energy transition strategies.

According to the contribution of the Working Group III to the Sixth Assessment Report from the IPCC [3], in mitigation scenarios which restrict warming to 1.5°C with no or limited overshoot, net zero $CO_2$ emissions must be reached around 2035 to 2070, and fossil oil use typically declines 30% to 78% by 2050 from 2020 levels. Thus, there is the risk of assets in oil refineries becoming stranded and no longer able to earn their economic return prior to the end of their lifetime [4]. Nevertheless, opportunities for the integration of the refining sector to the decarbonization context do exist [5]. This involves the processing of renewable feeds in refining units and the investment in small-scale modular refineries, as further detailed in Section 2.

According to Guedes (2019) [6], mathematical models have been used with several objectives in studies related to the refining sector, such as: evaluating crude oil selection, process configurations and the synthesis of products; planning of products' logistics; integrating refining and petrochemical plants; evaluating greenhouse gas (GHG) emissions in refineries; integrating oil supply chains; among others. Several studies applied optimization techniques using linear, non-linear or mixed integer programming [7], [8], [9], [10]. In terms of optimization models, it is worth highlighting the OURSE (Oil is Used in Refineries to Supply Energy) model [11], [12], which represents the refining sector at a global level. In addition to the models described above, there are others which are not focused on optimization but rather in the simulation of the sector [13], [14], [15]. Nevertheless, none of the existing tools focus on the optimization of the refining sector while considering possibilities such as using its assets for the processing of renewable feeds or investing in small-scale modular refineries. This is precisely the gap that the ORION model seeks to fill.

The main objectives of this work are, thus, to present the ORION model and to exemplify its application, focusing on the importance of innovative approaches for the refining sector in decarbonization scenarios.

## 2. General description of the model

ORION is a Mixed Integer Linear Programming (MIP) model developed in the GAMS (General Algebraic Modeling System) language using the CPLEX solver. It can be applied for any location, which can be further divided into sub-regions of interest. Also, external regions are accounted for to deal with external trade. The current version of the model operates from 2015 to 2040.

Fourteen refining process units are considered, as seen in Figure 1, as well as auxiliary units (the hydrogen generation and cogeneration units, HGU and COG, respectively). Up to three types of crudes (or their blends) can be defined, and ten types of final products are considered: refinery gas, LPG, naphtha, gasoline, kerosene, jet fuel oil, diesel, fuel oil, heating fuel oil and coke. Two campaigns[2] are comprised by the model, i.e., diesel and naphtha campaigns.

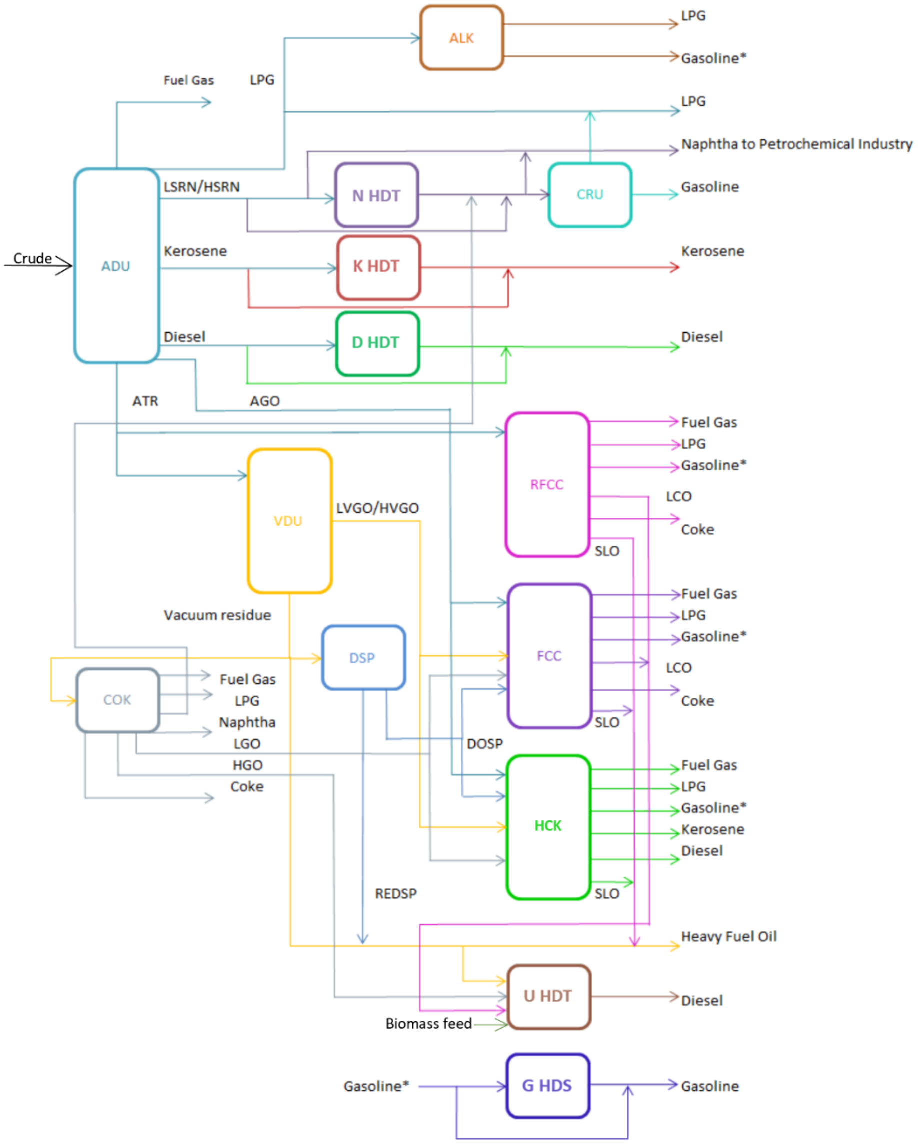

Figure 1. Refining scheme. Source: [6].

ADU – Atmospheric distillation unit; VDU – Vacuum distillation unit; DSP – Deasphalting unit; FCC – Fluid Catalytic Cracking unit; RFCC – Residue Catalytic Cracking unit; HCK – Hydrocracking unit; ALK – Alkylation unit; CRU – Catalytic Reforming unit; COK – Delayed Coking unit; GHDS – Gasoline Hydrodesulfurization unit; NHDT – Naphtha hydrotreating unit; KHDT – Kerosene hydrotreating unit; DHDT – Diesel hydrotreating unit; UHDT – Unstable products hydrotreating unit; LPG – Liquefied petroleum gas; LSRN – Light straight run naphtha; HSRN – Heavy straight run

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[2] A campaign is an operation mode that aims to maximize the production of a given product.

naphtha; AGO – Atmospheric gasoil; ATR – Atmospheric residue; LVGO – Light vacuum gasoil; HVGO – Heavy vacuum gasoil; LGO – Light gasoil; HGO – Heavy gasoil; DOSP – Deasphalted oil; REDSP – Deasphalted residue; LCO – Light cycle oil; SLO – Slurry oil.

In addition to the conventional operation of the refining sector – that is, the processing of crude oil in large-scale sites aiming mainly at synthesizing fossil fuels – ORION can also address innovative approaches such as the processing of renewable feeds and the investment in modular mini refineries. These are further explained in the paragraphs below.

Co-processing involves introducing a renewable feed alongside the traditional fossil feed in refining units, resulting in drop-in products containing a proportion of renewable carbon, but still an amount fossil carbon. ORION considers the possibility of biomass feeds (such as straight vegetable oils (SVOs), used cooking oils (UCOs) or animal fats) co-processing in hydrotreaters for unstable products (UHDTs). This approach is easily implementable within current facilities, utilizing existing infrastructure and configurations, with reduced need for additional capital investment [16]. Co-processing is regarded as a pathway to accelerate the transformation of oil refineries towards the synthesis of sustainable fuels [17], representing an important strategy for the growth of drop-in biofuel production [18].

Modular mini refineries are also considered in the model. Those are small-scale refineries (various definitions exist in the literature, ranging from 1,500 to 50,000 barrels/day) that consist of independently designed units [10]. Compared to conventional refineries, the small-scale modular concept offers significant advantages in the context of energy transition, such as: lower installation costs, shorter construction times and enhanced flexibility, allowing for easier upgrades to accommodate changes in product demand or incorporate innovations. Since small-scale refineries are simpler than large-scale ones, only a subset of the process units is available to the model, including the atmospheric and vacuum distillation units, all types of hydrotreaters, the catalytic reforming process, the fluid catalytic cracking unit and the auxiliary processes.

## 3. The optimization model: objective function and constraints

The objective function in ORION is the discounted total cost for meeting the demand for refining products across all regions and periods considered. ORION aims to obtain an optimal solution by minimizing this function subject to the energy and mass balances of the technologies, as well as to a set of constraints. These constraints are related to the availability of resources, to carbon dioxide emissions, to the quality of the final products, to the demand for final products, among others.

ORION allows a two-step optimization procedure. A first optimization round is performed to identify refineries with low utilization factors[3]. Afterwards, a second optimization round considers the closure of these refineries, since it is known that a minimum utilization factor is required for a refinery park to continue operating with acceptable margins [19].

Section 3.1 describes the objective function, while Section 3.2 describes equations related to the above-mentioned constraints. Finally, Section 3.3 lists all the data that must be inputted by the user to perform an analysis, as well as the outputs that result from the model.

### 3.1. The objective function

The objective function is divided into two parts, one concerning conventional large-scale refineries and the other one concerning modular mini refineries.

$$Z_{CR} = CAPEX_{CR} + OPEX_{CR} + OPC_{CR} + BIOPC_{CR} + FPC_{CR} + EPC_{CR} + CO2C_{CR} + INTTRAD_{CR} + IMP - EXP + CAPEXINFRA \tag{1}$$

$$Z_{MR} = CAPEX_{MR} + OPEX_{MR} + OPC_{MR} + BIOPC_{MR} + FPC_{MR} + EPC_{MR} + CO2C_{MR} + INTTRAD_{MR} \tag{2}$$

$$Z = Z_{CR} + Z_{MR} \tag{3}$$

In Equations 1 to 3, $Z_{CR}$ and $Z_{MR}$ represent the part of the objective function, $Z$, that refers to conventional large-scale refineries and to modular mini refineries, respectively. $Z_{CR}$ and $Z_{MR}$, in Equations 1 and 2, respectively, are sums of terms representing costs related to the refining sector. All these terms consist of the discounted sum of the respective costs for all regions and periods analyzed, as shown in the Annex A. $CAPEX$ refers to the cost of investing on new refining units, and $OPEX$ includes fixed and variable operating & maintenance costs of new and existing units. $OPC$, $BIOOPC$, $FPC$ and $EPC$ are the costs of purchasing crude oils, biomass oils, fuels and electricity. $CO2C$ refers to the cost of $CO_2$ emissions. $INTTRAD$, $IMP$, $EXP$ and $CAPEXINFRA$ are, respectively: the costs to trade final products in-between internal regions and to import them, the revenues with their exports and the capacity expansion costs for structures such as ports, which enable external trade. One should notice that the function for modular mini refineries does not include the $IMP$, $EXP$ and $CAPEXINFRA$ components, since

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[3] The utilization factor of a refinery is defined as the ratio between the amount of crude oil processed in its atmospheric distillation unit and the installed capacity of this unit.

those sites are supposed to provide its products locally. A full nomenclature list can be found in Annex C.

The elements of these equations are detailed below, and Annex A presents all the equations.

### 3.1.1. CAPEX

Capital Expenditures (CAPEX) are composed by ISBL (*Inside Battery Limits*) and OSBL (*Outside Battery Limits*) investments. The first category includes process units, piping, electrical installations, and instrumentation located in the unit area, while the second one encompasses distribution systems, storage facilities and other structures located outside the main process area. Equation A.1 in the Annex represents the CAPEX.

### 3.1.2. OPEX

Operating Expenditures (OPEX) include fixed and variable running costs. The first category encompasses labor, maintenance, taxes, insurance, and administrative expenses. The second one corresponds mainly to chemical products and catalysts (utilities are treated separately). Equation A.2 in the Annex represent the OPEX.

### 3.1.3. Oil purchase cost (OPC)

Each type of crude blend in the model has its price defined according to a crude oil reference price, to take into account the impact of the different oil qualities into their value. In general, the price of a type of crude oil is a function of its °API, of its sulfur level and of the Brent price [6]. This is described in Equation A.3 in the Annex of this work, which shows that each additional unity of °API results in a premium of around USD 0.002 per dollar of Brent, and each percent increase of sulfur leads to a discount of USD 0.056 per dollar of Brent.

The oil purchase cost is, then, defined based on the price of each crude oil blend, its import freight price and the quantity processed in each region and period of analysis, as described by Equation A.4 in the Annex of this work.

### 3.1.4. Biomass oil purchase cost (BIOOPC)

The biomass oil purchase cost in the model depends on its price, the price of its freight in between internal regions and the quantity processed in each region and period of analysis, as described by Equation A.5 in the Annex of this work.

### 3.1.5. Fuel purchase cost (FPC)

The fuel purchase cost refers to the cost of fuels to meet the demand of refineries. The model considers natural gas, refinery gas, fuel oil and petroleum coke as fuels, and Equation A.6 and A.7 in the Annex describe the calculations.

### 3.1.6. Electricity purchase cost (EPC)

The electricity purchase cost refers to the cost of grid electricity to meet the demand of refineries. Equation A.8 in the Annex describe the calculations.

### 3.1.7. $CO_2$ emissions cost (CO2C)

The cost of $CO_2$ emissions in the model depends on possible $CO_2$ pricing, that is, values to be paid for a given amount of emitted gas. Thus, the calculations are made based on a $CO_2$ price, and on the quantity of this gas released to the atmosphere by refineries, as described by Equation A.9 in the Annex of this work.

### 3.1.8. Cost of internal trade of refining products (INTTRAD)

Internal trade cost represents the trade of final refining products between internal regions. It includes the cost of transportation of a given product from one region to another, as shown in Equations A.10 in the Annex.

### 3.1.9. Cost of importing refining products (IMP)

Imports costs consider, for each product, FOB (Free-on-board) prices and the freight costs related to their transportation from an external region. Equation A.11 in the Annex details this calculation.

### 3.1.10. Revenues from exporting refining products (EXP)

Exports revenues consider, for each product, FOB (Free-on-board) prices. Equation A.12 in the Annex details this calculation.

### 3.1.11. Expansion costs for structures which enable external trade (CAPEXINFRA)

ORION allows the capacity expansion of infrastructure, such as harbors, through which external trade happens. This additional capacity has an associated CAPEX, and its costs are detailed in Equation A.13 in the Annex.

## 3.2.Constraints

### 3.2.1. Crude oil availability

Crude oil is the main feedstock for refineries in ORION. At a given period, the total consumption of a given type of crude must be inferior or equal to its availability. This is detailed in Equation A.14.

### 3.2.2. Balances of intermediate products, of streams and of final products

Three types of constraints guarantee the mass balances in a refinery. The equations for intermediate products balance input and output quantities in each unit, as shown in Figure 2 (top, left) and presented in Equation A.15 in the Annex. The equations for streams balance the output of a processing unit with their respective destinations, as pictured in Figure 2 (top, right) and shown in Equation A.16 in the Annex. The equations for products sum the streams that compose the pool of each final product, as illustrated in Figure 2 (bottom) and shown in Equation A.17 in the Annex.

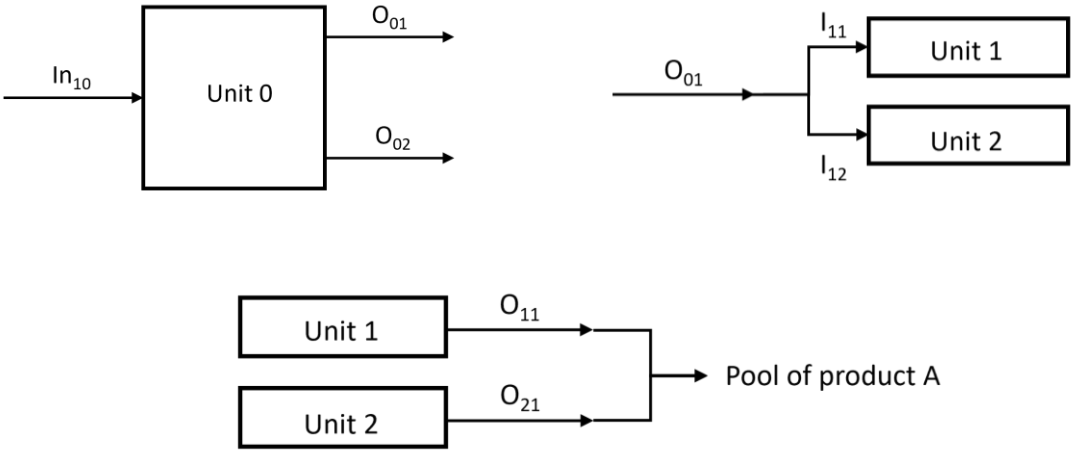

Figure 2. Top, left: flow diagram of the balance of intermediate products. Top, right: flow diagram of the balance of streams. Bottom: flow diagram of the balance of final products.

### 3.2.3. Capacity balances

The total nominal capacity of each processing unit in each region in the base year is an exogeneous variable. For each period, the updated nominal capacity is calculated by adding that from the preceding period to new capacity investments. The available capacity in each period results when the nominal capacity is multiplied by a capacity factor, which considers events such as maintenance shutdowns. Finally, the capacity level of a processing unit is equal to the sum of the input flows in the given unit and must be inferior to the available capacity. Equations A.18 to A.20 describe these calculations.

### 3.2.4. Demand for of utilities

**Steam**

Steam is divided into three types: high, medium, and low-pressure steam (HP, MP, and LP steam, respectively). Their demand is calculated considering the specific consumption of each unit in each region, period, and type of refinery. Their supply is provided using either cogeneration or boilers. In addition, MP steam can be supplied by HP steam surplus, and LP steam can be supplied by MP steam surplus. Equations A.21 to A.27 in the Annex describe the balance of different types of steam.

**Fuel**

Fuel demand is calculated considering the specific consumption of each unit in each region, period, and type of refinery. The supply can be provided by fuel oil or refinery gas, both produced in the refining process itself. Particularly, FCC and RFCC units apply the coke they produce. Equations A.28 to A.33 in the Annex describe the balance of fuels.

**Electricity**

Electricity demand is calculated considering the specific consumption of each unit in each region, period, and type of refinery. The supply can be provided by cogeneration or electricity purchased from the grid. Equations A.34 to A.36 in the Annex describe the electricity balance.

**Hydrogen**

Hydrogen demand is calculated considering the specific consumption of each unit in each region, period, and type of refinery. The supply can be provided by hydrogen generation units in addition to hydrogen produced in catalytic reforming units. Equations A.37 to A.39 in the Annex describe the hydrogen balance.

### 3.2.5. $CO_2$ emissions

ORION accounts for $CO_2$ emissions from refineries. These come from the burning of fuels (natural gas, refinery gas, fuel oil and coke) to produce steam, electricity, and heat, from the use of grid electricity, and from the production of hydrogen using natural gas. Equation A.40 in the Annex describes this calculation.

### 3.2.6. Quality specification of products

Some final products must meet technical quality specifications for given properties. ORION considers specifications for gasoline (density, sulfur content, octane number), diesel (density, sulfur content, cetane number) and jet fuel, kerosene, and fuel oil (sulfur content). Equation A.41 in the Annex describes the constraints related to these properties.

### 3.2.7. Demand for final products

For each final product in each region, it is necessary to guarantee that supply (acquisition from own production, acquisition from internal regions and imports) is greater or equal to the sum of demand and exports. Equation A.42 in the Annex describes this.

### 3.2.8. Constraints on imports and exports

Trade with external regions – that is, imports and exports – is restricted by the capacity of infrastructure to do so, such as harbors. For a given region and period, the sum of imports and exports of final products is limited to the total infrastructure capacity. It is important to mention that the model does allow the expansion of this infrastructure if needed. Equations A.43 and A.44 in the Annex describe these constraints.

### 3.2.9. Biomass co-processing

As stated in Section 2, ORION considers the possibility of biomass oil co-processing in hydrotreaters for unstable products (UHDTs). The biomass oil available for co-processing, in each region is defined by the amount of this oil which is produced in the region together with that which is acquired from other regions and subtracted from that which is sold to other regions. This is represented by Equation A.45 in the Annex.

The actual amount of biomass oil inputted in UHDT units is also restricted by the mass fraction that can be fed to the unit. Studies indicate the possibility of working with different percentages of biomass raw material in the input of UHDTs, with the potential to reach 100% renewable feedstock [16]. Equation A.46 in the Annex describes this constraint.

It is also relevant to point out that the removal of undesirable elements through hydrotreating becomes more challenging when comparing oxygen with sulfur, being more demanding in terms of catalysts and required pressure. Thus, biomass-derived compounds, which have a high oxygen content in their composition, require more severe conditions in this process [20]. Therefore, operating with a fraction of renewable feeds might increase the operating costs and the required hydrogen pressure of UHDT units. This is represented in equations A.47 and A.48 in the Annex.

### 3.2.10. Modular mini refineries

Most of the cost and constraint functions described in the sections above must be defined both for conventional large-scale refineries and for modular mini refineries, as is clear by the analysis of the equations in Annex A. Nevertheless, the definition of modular mini refineries requires one special constraint. While large-scale refineries are treated by ORION in a continuous manner – that is, for each region the capacity of each type of unit is a number that broadly represents the sum of all refineries in the region – modular mini refineries consist of independently designed units with pre-defined capacities. So, it is important to have a mathematical representation of the integer number of these small-scale refineries and of their typical capacity. This is defined by Equation A.49 in the Annex, which transforms the model into a Mixed Integer Linear Programming model (MIP).

## 3.3.Input data and output results

ORION is supported by an Excel sheet in which it is possible to define all the necessary data for the analysis. This sheet is then read by the model. The data is separated into different categories, as shown in Figure 3: number of regions, crude oil definition, renewable oil definition, refining operations definition, modular mini refineries definition, intermediate products definition, final products definition, and economic settings. Table 1 details the data to be defined in each category.

As also shown by Figure 3, ORION outputs a series of results, which enable analyses such as:

- the evaluation of the amount of feedstocks (crude or biomass oils) by the refining sector over time and in different regions;
- the analysis of the installed capacity of units and of the capacity effectively used over time and in different regions, shedding light on potential stranded assets;
- the evaluation of the consumption of utilities and of the $CO_2$ emitted by the operation of refineries (which is mainly related to energy consumption) used over time and in different regions, providing insight into possible mitigation measures;
- analysis of how the demand is met in each period and region: own production by the region, trade with other internal regions or imports from external regions;

- evaluation of different types of costs over periods and regions: CAPEX and OPEX of refineries, purchasing of feedstocks and utilities, $CO_2$ pricing and costs with internal and external trade.

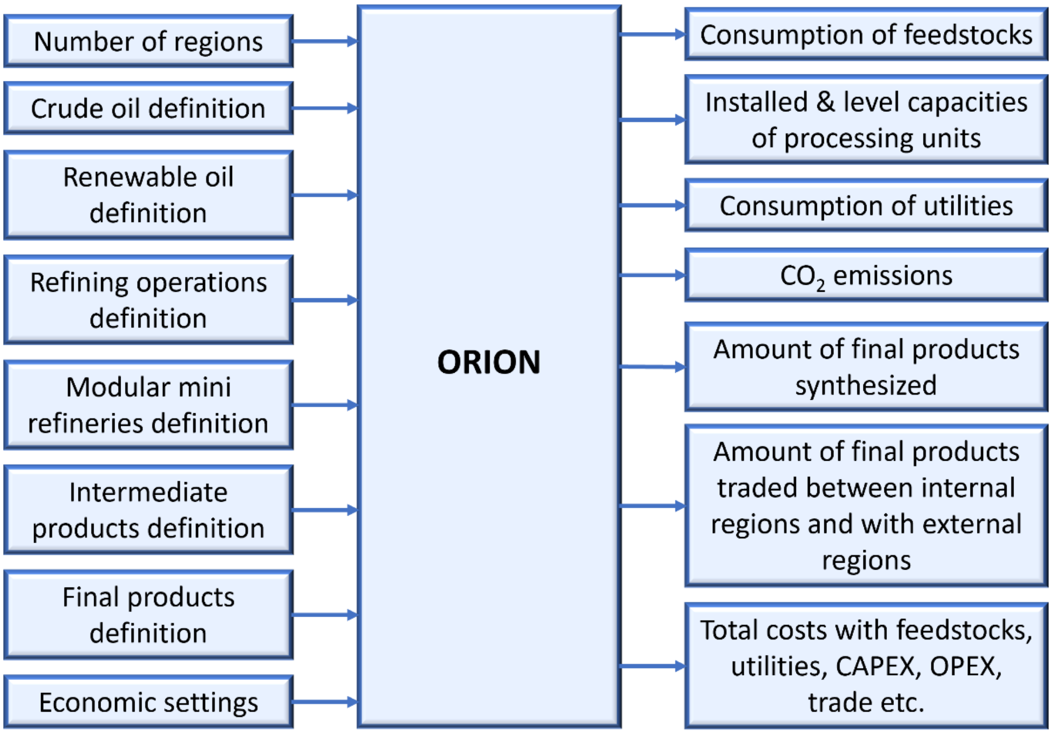

Figure 3. ORION input data and output results.

Table 1. ORION Input data.

| **Category** | **Input data** |
|---|---|
| Number of regions | • Number of internal regions<br>• Number of external regions |
| Crude oil definition | • Maximum availability of each blend<br>• API gravity and sulfur content of each blend<br>• Reference crude oil FOB price and growth rates<br>• Crude oil freight prices |
| Renewable oil definition | • Maximum availability and growth rates<br>• Reference price and growth rates<br>• Freight prices<br>• Maximum mass fraction to be fed in UHDT units |
| Refining operations definition | • Installed capacities of units (base year)<br>• CAPEX and OPEX of units<br>• Yields of units<br>• Specific consumption of utilities<br>• Prices of fuels and electricity<br>• Emission factors of fuels and electricity<br>• $CO_2$ taxation price |
| Modular mini refineries definition | • Installed capacities of units (base year)<br>• Typical ADU capacity<br>• CAPEX and OPEX of units |
| Intermediate products definition | • Properties of intermediate products that compose the final pool of gasoline, kerosene, jet fuel, diesel and fuel oil[1] |
| Final products definition | • Initial demand and growth rates<br>• Required properties of final products: gasoline, kerosene, jet fuel, diesel and fuel oil[1]<br>• Final products FOB import/export prices and growth rates<br>• Final products freight prices<br>• Installed capacity of infrastructure for final products transport (base year)<br>• Cost of expanding infrastructure for final products transport |
| Economic settings | • Discount rate |

[1] Gasoline: density, sulfur content, octane number; diesel: density, sulfur content, cetane number; jet fuel, kerosene, and fuel oil: sulfur content.

## 4. Example of application

Below is a case study using ORION. As highlighted in Section 3, there are various types of results that can be obtained from the model. The example discussed here aims to demonstrate the model's functionality and focuses primarily on evaluating installed capacities of units and their utilization levels, as well as assessing the consumption of biomass oils in HDT units.

### 4.1. Definition and objectives

As stated in Section 1, decarbonization scenarios imply that fossil oil use must decline in the following decades, leading to a decrease in the utilization of refineries. In general, it is understood that a refinery park shall have 70 – 80% as a minimum utilization factor to operate with acceptable margins. Refineries operating with low utilization rates, thus, might need to be shut down [19].

The present case study focuses on the Brazilian refining sector under a decarbonization scenario. In this example, the two-step procedure described in Section 3 was used, and it was established that large-scale refineries operating with utilization rates lower than 50% shall be closed. The objective of this study was to evaluate if these closures help keep the remaining sites with high utilization rates, and if biomass co-processing and modular mini refineries - innovative approaches for the sector in decarbonization scenarios - play a role in the energy transition context.

### 4.2. Methods

The decarbonization case evaluated was originally defined by Guedes (2019) [6], as a scenario that considers an accelerated energy transition towards climate change. Brazil was divided in four regions[4], illustrated in Figure 4, along with the refineries in which one of them. Demands were constructed based on the “Sustainable Development” scenario of the World Energy Outlook studies [21] and on premises regarding the Brazilian transport sector [22]. Despite Brazil having only large-scale refineries processing fossil oil in the base year, options for the sector's evolution over the years include the co-processing of soybean SVO in UHDT units, as well as expansion through modular mini-refineries. All the relevant data regarding the case definition – demand for final products, SVO availability etc. – is described in Annex B of this work.

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[4] South region (S); Rio de Janeiro Minas Gerais and Espírito Santo states (RJ/MG/ES); São Paulo state (SP); North, Northeast and Midwest regions (N/NE/CO).

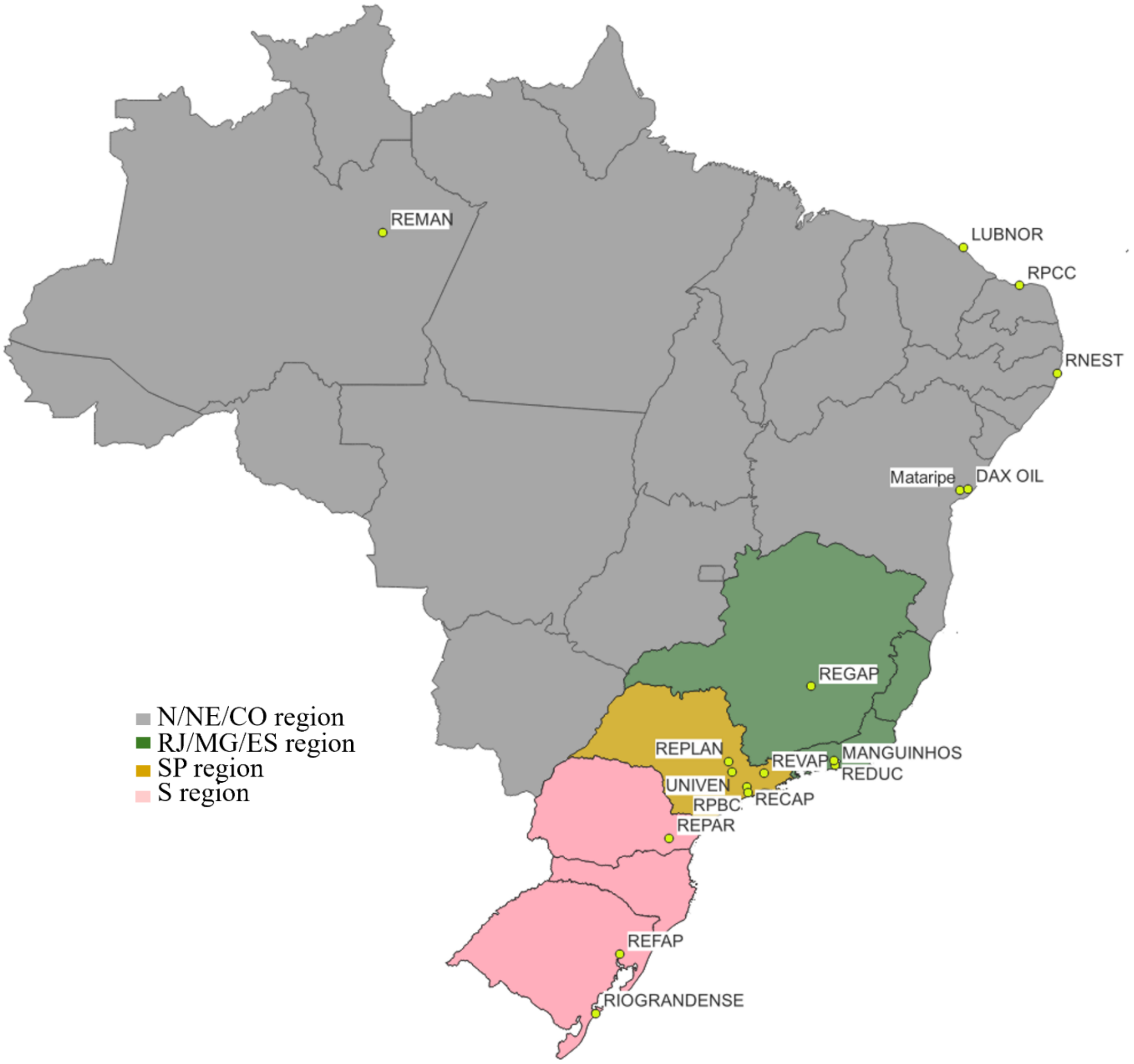

Figure 4. Brazilian sub-regions and refineries.

To assess the closure of refineries with low utilization rates, a two-step optimization process was implemented. Initially, a preliminary simulation identified regions where the utilization rate dropped below 50% during a specific period. Following this, a second run was executed, with utilization factors in the identified regions constrained to zero in the periods following those that presented low utilization rates. This second run started from the results of the previous one.

### 4.3. Results and discussion

Figure 5 illustrates that large-scale refineries in the South and RJ/MG/ES regions exhibit utilization factors below 50% in 2025 and 2030, respectively, leading to their closure in subsequent years. Moreover, the utilization factor of large-scale refineries in the N/NE/CO region drops to zero by 2035. The SP region maintains a utilization factor above 80%, that is, in fact the remaining sites are pushed to higher levels of utilization.

Additionally, modular mini refineries are installed in the South and N/NE/CO regions to help meeting the demand.

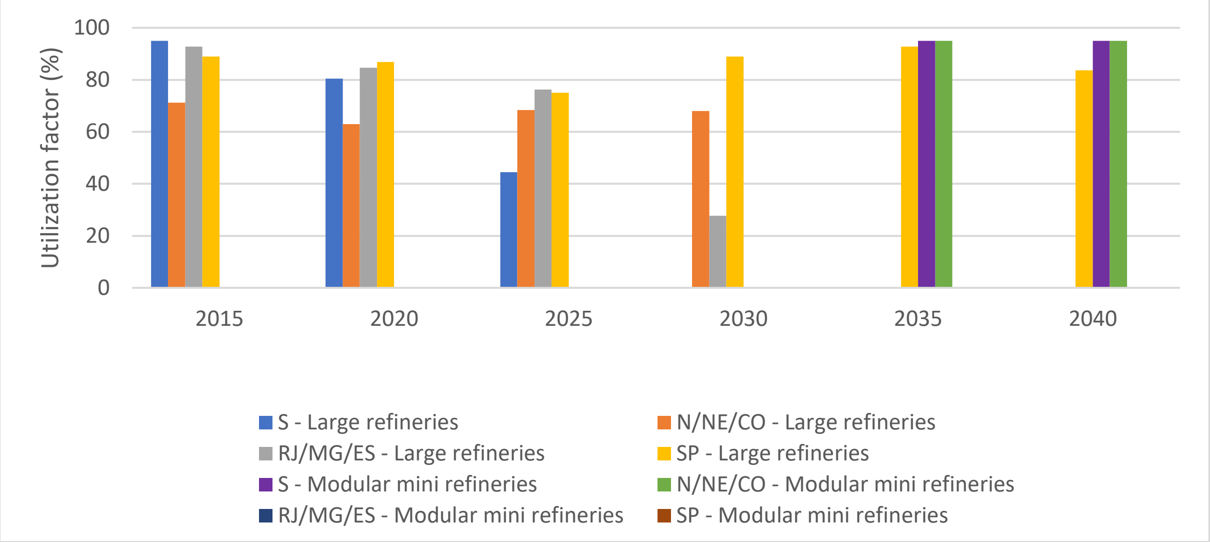

Figure 5. Utilization factor of Brazilian refineries.

Figure 6 shows that SVO co-processing is present from 2025 on in all regions where refineries are operating, both for large-scale and for modular mini refineries. It is important to point out that, the South and N/NE/CO regions, where small-scale refineries are installed, are also the regions with more SVO availability.

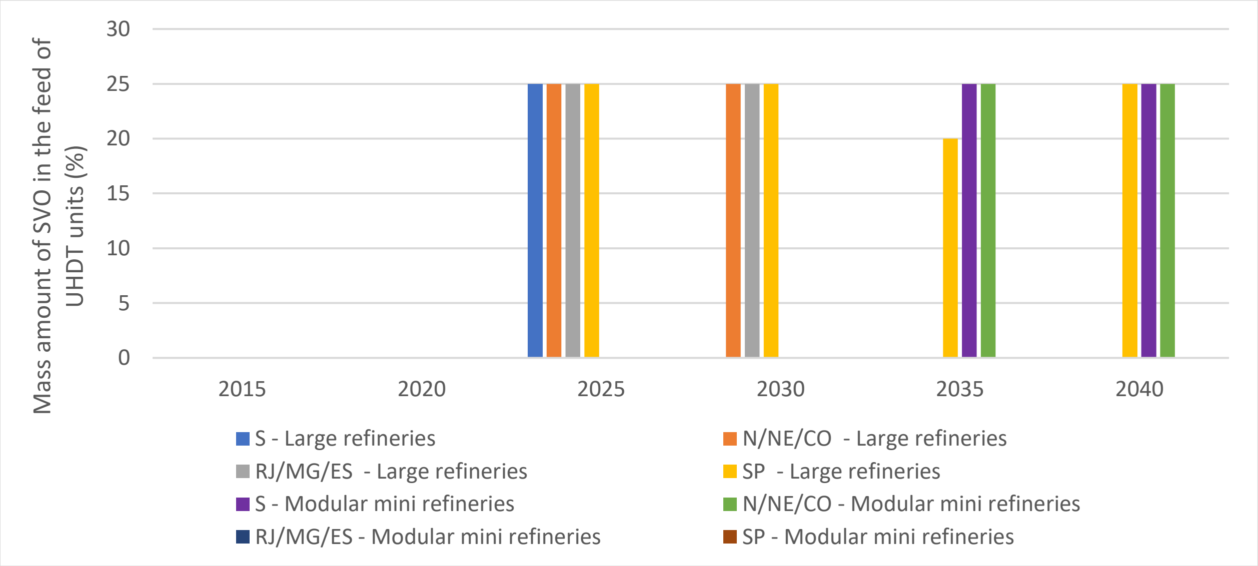

Figure 6. Mass amount of SVO in the feed of UHDT units in Brazil.

## 5. Final remarks

This work introduced the optimization procedure within ORION (*Oil and renewables Refining Industry Optimization and syNergies*), a model designed for the analysis of the refining sector. Furthermore, an illustrative application example was presented. The model novelty comes mainly from the inclusion of opportunities like biomass co-processing in refining units and investment in small-scale modular refineries. In addition, the model allows a two-step optimization to identify refineries with low utilization factors and subsequently evaluate how the industry responds to their closure. This feature is particularly useful in the context of energy transition since a decline in fossil oil use is expected.

ORION is a flexible model that can be applied to various regions (countries, groups of countries, or country regions), provided that the necessary data is available. It can accommodate different refining schemes and campaigns, various types of crude oil, as well as oils derived from biomass, and refineries of different scales (large-scale or modular mini). In addition, it outputs a series of results which enable the analysis of: consumption of feedstocks; installed and level capacities of processing units; consumption of utilities; $CO_2$ emissions; amount of final products synthesized, traded inside the main region, and traded with external regions; and costs with feedstocks, utilities, CAPEX, OPEX and trade, among others.

The case study showed that closures of refineries with low utilization factors – which happen as demand for the final products of refineries decreases in decarbonization scenarios – do push the remaining sites to higher levels of utilization. The installation of modular mini refineries is a possibility for helping meet the demand as refineries are shutdown. In addition, biomass co-processing is a possibility for both large and small-scale refineries, meaning that drop-in products containing a proportion of renewable carbon can be obtained directly in refining sites.

This brief example shows that the ORION model is useful for understanding the evolution and integration of the refining sector to energy transition strategies and helps evaluating risks – such as that of stranded assets and closures of refineries – and opportunities – such as biomass co-processing and small-scale refineries – associated with this industry.

Next steps of development of the model include: the addition of other biomass co-processing options (e.g., other feedstocks sources and their use in other processing units, such as FCCs) and additional possibilities for the refining sector to integrate with the chemical sector (e.g., the production of ethylene, propylene and aromatics in refining units). This way, an even more comprehensive understanding of the potentialities for the refining sector in decarbonization scenarios will be possible.

## A. Annex A: Model equations

In the following equations, $X$ represents an amount of feedstock or utility; $P$ represents an amount of final product; $In$ corresponds to a quantity inputted in a process unit; $O$ is an output quantity of a process unit; $I$ and $E$ represent, respectively, imported and exported quantities; and $Av$ corresponds to the availability of a feedstock.

The subscript $rt$ represents the refinery type, that is, conventional large-scale or modular mini refineries ($CR$ or $MR$, respectively). $k$, $j$, $i$ and $n$, correspond input feeds, process units, intermediate products, and final products, respectively. $pt$ corresponds to a type of product. $er$, $ir$ and $t$ represent external regions, internal regions, and periods of time, respectively.

As the model is forecasted for future years, reference cost values are considered and brought to the base year through the net present value method, being $r$ the discount rate. $CRF$ is the capital recovery factor.

Other variables are described through the next sections, and a full nomenclature list can be found in Annex C.

### A.1. The objective function

#### A.1.1. CAPEX

$$CAPEX_{rt} = \sum_{j,ir,t} \frac{(ISBL_{rt,j} + OSBL_{rt,j}) \cdot AddCap_{rt,j,ir,t}}{(1+r)^{t-t_0}} \tag{A.1}$$

In these equations, $ISBL_{rt,j}$ and $OSBL_{rt,j}$ consist of the ISBL and OSBL costs related to the unit $j$ in the refinery type $rt$. $AddCap_{rt,j,ir,t}$ is the additional capacity of the process unit $j$ in the refinery type $rt$ in each region $ir$ and period $t$.

#### A.1.2. OPEX

$$OPEX_{rt} = \left( \sum_{j(\neq UHDT),ir,t} \left(1 + \frac{1}{CRF}\right) \cdot \frac{(FOM_{rt,j} + VOM_{rt,j}) \cdot LevelCap_{rt,j,ir,t}}{(1+r)^{t-t_0}} \right) + OPEX_{rt,UHDT} \tag{A.2}$$

In these equations, $FOM_{rt,j}$ and $VOM_{rt,j}$ consist of the fixed and operating costs related to the unit $j$ in the refinery type $rt$. $LevelCap_{rt,j,ir,t}$ is the capacity level of the process unit $j$ in the refinery type $rt$ in each region $ir$ and period $t$. $OPEX_{rt,UHDT}$ is the OPEX associated with the UHDT unit[5].

### A.1.3. Oil purchase cost (OPC)

$$Price_{oiltype,t} = \left(0.002 \cdot \Delta\, {}^{o}API_{oiltype,ref} - 0.056 \cdot \Delta Sulfur_{oiltype,ref}\right) \cdot Price_{ref,t} \qquad \text{(A.3)}$$

$$OPC_{rt} = \sum\nolimits_{oiltype,ir,t} \left(1 + \frac{1}{CRF}\right) \cdot \frac{\left(Price_{oiltype,t} + FreightPrice_{oiltype,er,ir,t}\right) \cdot X_{rt,oiltype,ir,t}}{(1+r)^{t-t_0}} \qquad \text{(A.4)}$$

In Equation A.3, for each period $t$, $Price_{oiltype,t}$ represents the price of the crude oil of interest, $\Delta\, {}^{o}API_{oiltype,ref}$ and $\Delta Sulfur_{oiltype,ref}$ are the differences between the properties of this crude oil and of the reference oil, and $Price_{ref,t}$ is the price of the reference oil. In Equation A.4, $Price_{oiltype,t}$ is the price of the representative oil as calculated in Equation A.3, $FreightPrice_{oiltype,er,ir,t}$ is the price of transporting this oil from external region $er$ to internal region $ir$ in period $t$, and $X_{rt,oiltype,ir,t}$ is the amount processed of this oil in refinery type $rt$ in the same region and period.

### A.1.4. Biomass oil purchase cost (BIOPC)

$$BIOPC_{rt} = \sum\nolimits_{ir_{ab},t} \left(1 + \frac{1}{CRF}\right) \cdot \frac{\left(Price_{biotype,ir_a,t} + FreightPrice_{biotype,ir_{ab},t}\right) \cdot X_{rt,biotype,ir_b,t}}{(1+r)^{t-t_0}} \qquad \text{(A.5)}$$

In Equation A.5, $Price_{biotype,ir_a,t}$ is the price of the biomass oil of interest in internal region $ir_a$ and in period $t$, $FreightPrice_{biotype,ir_{ab},t}$ is the price of transporting this oil to internal region $ir_b$ in period $t$, and $X_{rt,biotype,ir_b,t}$ is the amount processed of this oil in refinery type $rt$ in region $ir_b$.

### A.1.5. Fuel purchase cost (FPC)

$$FPC_{rt} = \sum\nolimits_{ir,t} \left(1 + \frac{1}{CRF}\right) \cdot \frac{\left(Price_{NG,t} \cdot X_{rt,NG,ir,t}\right) + \left(Price_{RG,t} \cdot X_{rt,RG,ir,t}\right) + \left(Price_{FO,t} \cdot X_{rt,FO,ir,t}\right) + \left(Price_{CK,e,t} \cdot X_{rt,CK,ir,t}\right)}{(1+r)^{t-t_0}} \qquad \text{(A.6)}$$

Considering an internal region $ir$ and a period $t$, the total fuel purchase cost considers the prices of natural gas, refinery gas, fuel oil and coke – respectively $Price_{NG,t}$, $Price_{RG,t}$, $Price_{FO,t}$,

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[5] See Section A.2.9 for its definition.

$Price_{Coke,t}$ – and the corresponding consumed amounts in refinery type $rt$ – $X_{rt,NG,ir,t}$, $X_{rt,RG,ir,t}$, $X_{rt,FO,ir,t}$ and $X_{rt,CK,ir,t}$.

While refinery gas and fuel oil are consumed only by process units, and coke is exclusively used in FCC and RFCCs, natural gas serves multiple purposes. It is utilized in cogeneration units and boilers for steam production, as well as in hydrogen generation units. Therefore, $X_{rt,NG,ir,t}$ is defined by the following equation:

$$X_{rt,NG,ir,t} = X_{rt,NGCOG,ir,t} + X_{rt,NGBoiler,ir,t} + X_{rt,NGHGU,ir,t} \qquad \text{(A.7)}$$

$X_{rt,\boldsymbol{NGCOG},ir,t}$, $X_{rt,\boldsymbol{NGBoiler},ir,t}$ and $X_{rt,\boldsymbol{NGHGU},ir,t}$ are, respectively, the amount of natural gas consumed in cogeneration units, boilers and hydrogen generation units.

### A.1.6. Electricity purchase cost (EPC)

$$EPC_{rt} = \sum_{ir,t} \left(1 + \frac{1}{CRF}\right) \cdot \frac{\left(Price_{GE,t} \cdot X_{rt,GE,ir,t}\right)}{(1+r)^{t-t_0}} \qquad \text{(A.8)}$$

Considering an internal region $ir$ and a period $t$, the total grid electricity purchase cost considers the price of grid electricity, $Price_{GE,t}$, and its consumed amount in refinery type $rt$, $X_{rt,GE,ir,t}$.

### A.1.7. CO2 emissions cost (CO2C)

$$CO2C_{rt} = \sum_{ir,t} \left(1 + \frac{1}{CRF}\right) \cdot \frac{\left(PriceCO2_t \cdot CO2Emissions_{rt,ir,t}\right)}{(1+r)^{t-t_0}} \qquad \text{(A.9)}$$

Considering an internal region $ir$ and a period $t$, the total cost with $CO_2$ emissions is calculated based on the $CO_2$ taxation price, $PriceCO2_t$, and its total emissions in refinery type $rt$, $CO2Emissions_{rt,ir,t}$.

### A.1.8. Cost of internal trade of refining products (INTTRAD)

$$INTTRAD_{rt} = \sum_{n,ir_{ab},t} \left(1 + \frac{1}{CRF}\right) \cdot \frac{\left(FreightPrice_{n,ir_{ab},t} \cdot P_{rt,n,ir_{ab},t}\right)}{(1+r)^{t-t_0}} \qquad \text{(A.10)}$$

For every pair of internal regions $ir_{ab}$ and a period $t$, $FreightPrice_{n,ir_{ab},t}$ is the freight price of product $n$ between regions $a$ and $b$, and $P_{rt,n,ir_{ab},t}$ is the amount of it which is transported between the regions.

### A.1.9. Cost of importing refining products (IMP)

$$IMP = \sum_{n,er,ir,t} \left(1 + \frac{1}{CRF}\right) \cdot \frac{\left(FOBPrice_{n,t} + FreightPrice_{n,er,ir,t}\right) \cdot I_{n,er,ir,t}}{(1+r)^{t-t_0}} \qquad \text{(A.11)}$$

For an internal region $ir$, an external region $er$ and a period $t$, $FOBPrice_{n,t}$ is the free-on-board price of the imported product $n$, $FreightPrice_{n,er,ir,t}$ is the freight price for importing this product and $I_{n,er,ir,t}$ is the quantity which is imported.

### A.1.10. Revenues from exporting refining products (EXP)

$$EXP = \sum_{n,er,ir,t} \left(1 + \frac{1}{CRF}\right) \cdot \frac{\left(FOBPrice_{n,t}\right) \cdot E_{n,er,ir,t}}{(1+r)^{t-t_0}} \qquad \text{(A.12)}$$

For an internal region $ir$, an external region $er$ and a period $t$, $FOBPrice_{n,t}$ is the free-on-board price of the exported product $n$ and $E_{n,er,ir,t}$ is the quantity which is exported.

### A.1.11. Expansion costs for structures which enable external trade (CAPEXINFRA)

$$CAPEXINFRA = \sum_{pt,t} \frac{\left(CostAddInfra_{pt}\right) \cdot AddCapInfra_{pt,t}}{(1+r)^{t-t_0}} \qquad \text{(A.13)}$$

For a period $t$ and a product type $pt$, $CostAddInfra_{pt}$ is the cost of additional infrastructure (e.g., harbors) needed for importing and/or exporting this kind of product, and $AddCapInfra_{pt,t}$ is the required additional capacity. For simplicity, three types of products are considered: light (LPG, naphtha and gasoline), medium (kerosene, jet fuel oil, diesel, fuel oil and heating fuel oil) and heavy (petroleum coke).

## A.2. Constraints

### A.2.1. Crude oil availability

$$\sum_{rt,ir} X_{rt,oiltype,ir,t} \leq Av_{oiltype,t} \qquad \text{(A.14)}$$

Given a type of crude $oiltype$ and a period $t$, the sum of the amount processed in all refinery types $rt$ and considering all supply internal regions $ir$, $X_{rt,oiltype,ir,t}$, must be inferior or equal to the availability of this crude in the period, $Av_{oiltype,t}$.

### A.2.2. Balances of intermediate products, of streams and of final products

$$\alpha_{rt,j,i} \cdot \sum\nolimits_{k} In_{rt,k,j,ir,t} = O_{rt,j,i,ir,t} \tag{A.15}$$

$$O_{rt,j,i,ir,t} = \sum\nolimits_{j} In_{rt,j,i,ir,t} \tag{A.16}$$

$$P_{rt,n,ir,t} = \sum\nolimits_{i,j} O_{rt,j,i,ir,t} \tag{A.17}$$

For a given refinery type $rt$, in an internal region $ir$ and period $t$, in Equation A.15, $\alpha_{rt,j,i}$ is the yield of the intermediate product $i$ in the processing unit $j$, $In_{rt,k,j,ir,t}$ is the quantity of input feed $k$ in the processing unit $j$ and $O_{rt,j,i,ir,t}$ is the quantity of intermediate product $i$ outputted by processing unit $j$. In Equation A.16, $In_{rt,j,i,ir,t}$ is the quantity of intermediate product $i$ routed to other units $j$. Finally, in Equation A.17, $P_{rt,n,ir,t}$ is the amount of final product $n$, and $O_{rt,j,i,ir,t}$ is the amount of intermediate product $i$ in the processing unit $j$ which composes the pool of $n$.

### A.2.3. Capacity balances

$$Cap_{rt,j,ir,t0} = CF_{rt,j,ir,t0} \cdot NomCap_{rt,j,ir} \tag{A.18}$$

$$Cap_{rt,j,ir,t(\neq to)} = CF_{rt,j,ir,t} \cdot \left( NomCap_{rt,j,ir} + \sum_{t} AddCap_{rt,j,ir,t} \right) \tag{A.19}$$

$$LevelCap_{rt,j,ir,t} = \sum\nolimits_{k} In_{rt,k,j,ir,t} \tag{A.20}$$

For a given refinery type $rt$, in an internal region $ir$ and in the base year $t0$, $CF_{rt,j,ir,t0}$ is the capacity factor of the process unit $j$ and $NomCap_{rt,j,ir}$ is its nominal capacity, defining the available capacity, $Cap_{rt,j,ir,t0}$, according to Equation A.18. For future periods $t$, $CF_{rt,j,ir,t}$ is the capacity factor of the process unit $j$ and $AddCap_{rt,j,ir,t}$ is the additional capacity due to new investments, which define the available capacity, $Cap_{rt,j,ir,t(\neq to)}$, according to Equation A.19. Finally, $In_{rt,k,j,ir,t}$ is the quantity of input feed $k$ in the processing unit j, which defines the level capacity, $LevelCap_{rt,j,ir,t}$, according to Equation A.20.

### A.2.4. Demand for utilities

**Steam**

$$DEM_{rt,st,ir,t} = \sum_j SC_{rt,st,j,ir,t} \cdot LevelCap_{rt,j,ir,t} \tag{A.21}$$

$$P_{rt,HP,ir,t} = DEM_{rt,HP,ir,t} + Exc_{rt,HP,ir,t},\ P_{rt,HP,ir,t} \geq 0, Exc_{rt,HP,ir,t} \geq 0 \tag{A.22}$$

$$P_{rt,MP,ir,t} + Exc_{rt,HP,ir,t} = DEM_{rt,MP,ir,t} + Exc_{rt,MP,ir,t},\ P_{rt,MP,ir,t} \geq 0, \\ Exc_{rt,MP,ir,t} \geq 0 \tag{A.23}$$

$$P_{rt,LP,ir,t} + Exc_{rt,MP,ir,t} \geq DEM_{rt,LP,ir,t},\ P_{rt,LP,ir,t} \geq 0 \tag{A.24}$$

In Equations A.21 to A.24, for a given steam type $st$ (high, medium, or low-pressure steam), a given refinery type $rt$, in an internal region $ir$ and period $t$, $DEM_{rt,st,ir,t}$ is the total demand for that type of steam, $SC_{rt,st,j,ir,t}$ is its specific consumption in process unit $j$, and $LevelCap_{rt,j,ir,t}$ is the level capacity of the unit.

In Equation A.22, $P_{rt,HP,ir,t}$ is the total production of high-pressure steam, which must encompass the demand for this type of steam and might also result in some excess amount, $Exc_{rt,HP,ir,t}$. Equation A.23 defines $P_{rt,MP,ir,t}$ as the total production of medium-pressure steam, which, together with any available high-pressure steam excess – $Exc_{rt,HP,ir,t}$ –, must encompass the demand for this type of steam and might also result in some excess amount, $Exc_{rt,MP,ir,t}$. Finally, Equation A.24 defines $P_{rt,LP,ir,t}$ as the total production of low-pressure steam, which, together with any available medium-pressure steam excess – $Exc_{rt,MP,ir,t}$ –, must encompass the demand for this kind of steam.

Considering a refinery type $rt$, an internal region $ir$ and a period $t$, the production of steam, $P_{rt,st,ir,t}$ in Equation A.25 below, comes either from cogeneration, $SteamCOG_{rt,st,ir,t}$, or boilers, $SteamBoilers_{rt,st,ir,t}$.

$$P_{rt,st,ir,t} = SteamCOG_{rt,st,ir,t} + SteamBoilers_{rt,st,ir,t} \tag{A.25}$$

$$SteamCOG_{rt,HP,ir,t} = X_{rt,NGCOG,ir,t} \cdot TurbineEff\ \cdot COGSteamEff \tag{A.26}$$

$$SteamBoiler_{rt,st,ir,t} = X_{rt,st,NGBoiler,ir,t} \cdot BoilerEff \tag{A.27}$$

Equation A.26 describes the cogeneration process, with $X_{rt,NGCOG,ir,t}$ being the amount of natural gas used in cogeneration units, $TurbineEff$, the efficiency of the turbine, and $SteamEff$, the steam production efficiency. Equation A.27 describes the boiler, with $X_{rt,st,NGBoiler,ir,t}$ being the amount of natural gas consumed and $BoilerEff$, its efficiency.

**Fuel**

$$DEM_{rt,Fuel,ir,t} = \sum_{j(\neq FCC,RFCC)} SC_{rt,Fuel,j,ir,t} \cdot LevelCap_{rt,j,ir,t} \tag{A.28}$$

$$DEM_{rt,Fuel,ir,t} = X_{rt,FO,ir,t} + X_{rt,RG,ir,t} \tag{A.29}$$

$$X_{rt,FO,ir,t} \leq P_{rt,FO,ir,t} - Dem_{FO,ir,t} \tag{A.30}$$

$$X_{rt,RG,ir,t} \leq P_{rt,RG,ir,t} \tag{A.31}$$

$$\begin{aligned} DEM_{rt,CK,ir,t} = {} & SC_{rt,CK,FCC,ir,t} \cdot LevelCap_{rt,FCC,ir,t} \\ & + SC_{rt,CK,RFCC,ir,t} \cdot LevelCap_{rt,RFCC,ir,t} \end{aligned} \tag{A.32}$$

$$DEM_{rt,CK,ir,t} = X_{rt,CK,ir,t}$$

$$X_{rt,CK,ir,t} \leq P_{rt,CK,ir,t} - Dem_{CK,ir,t} \tag{A.33}$$

Considering a refinery type $rt$, an internal region $ir$ and a period $t$, $DEM_{rt,Fuel,ir,t}$ is the demand for fuel, $SC_{rt,Fuel,j,ir,t}$ is the specific fuel consumption in the process unit $j$ and $LevelCap_{rt,j,ir,t}$ is the level capacity of the process unit $j$. $X_{rt,FO,ir,t}$ and $X_{rt,RG,ir,t}$ are the quantities of fuel oil and refinery gas used to meet fuel demand. $P_{rt,FO,ir,t}$ is the amount of fuel oil produced, which must encompass both the amount of fuel oil in refineries, $X_{rt,FO,ir,t}$, and its requirement by demand regions, $Dem_{FO,ir,t}$. $P_{rt,RG,ir,t}$ is the amount of refinery gas produced which must encompass the amount required in refineries. $DEM_{rt,CK,ir,t}$ is the demand for coke, $SC_{rt,CK,j,ir,t}$ is the specific fuel consumption in the process unit $j$ (FCC or RFCC) and $LevelCap_{rt,j,ir,t}$ is the level capacity of the same process unit. $X_{rt,CK,ir,t}$ is the quantity of coke used to meet fuel demand. $P_{rt,CK,ir,t}$ is the amount of coke produced, which must encompass both the demand for coke in refineries, $DEM_{rt,CK,ir,t}$, and its requirement by demand regions, $Dem_{CK,ir,t}$.

**Electricity**

$$DEM_{rt,Elec,ir,t} = \sum_{j} SC_{rt,Elec,j,ir,t} \cdot LevelCap_{rt,j,ir,t} \tag{A.34}$$

$$ElecCOG_{rt,ir,t} + ElecGrid_{rt,ir,t} \geq DEM_{Elec,rt,s,t}, , ElecCOG_{rt,ir,t} \leq LevelCap_{rt,COG,ir,t} \tag{A.35}$$

$$ElecCOG_{rt,s,t} = X_{rt,NGCOG,ir,t} \cdot TurbineEff \ \cdot COGElecEff \tag{A.36}$$

Considering a refinery type $rt$, an internal region $ir$ and a period $t$, $DEM_{rt,Elec,s,t}$ is the demand for electricity, $SC_{rt,Elec,j,ir,t}$ is the specific electricity consumption in the process unit $j$ and $LevelCap_{rt,j,ir,t}$ is the level capacity of the process unit $j$. $ElecCOG_{rt,ir,t}$ is the amount of electricity produced by cogeneration and $ElecGrid_{rt,ir,t}$ is the amount of electricity purchased from the grid. Together, they must encompass the demand for electricity. Equation A.36 describes the cogeneration process, with $X_{rt,NGCOG,ir,t}$ being the amount of natural gas used in cogeneration units, $TurbineEff$, the efficiency of the turbine, and $ElecEff$, the electricity production efficiency.

**Hydrogen**

$$DEM_{rt,H2,ir,t} = \left(\sum_{j(\neq UHDT)} SC_{rt,H2,j,ir,t} \cdot LevelCap_{rt,j,ir,t}\right) + DEM_{rt,H2,UHDT,ir,t} \tag{A.37}$$

$$P_{rt,H2,ir,t} \geq DEM_{rt,H2,ir,t} \tag{A.38}$$

$$P_{rt,H2,ir,t} = \alpha_{rt,H2,HGU} \cdot LevelCap_{rt,HGU,ir,t} + \alpha_{rt,H2,CRU} \cdot LevelCap_{rt,CRU,ir,t} \tag{A.39}$$

Considering a refinery type $rt$, an internal region $ir$ and a period $t$, $DEM_{rt,H2,ir,t}$ is the demand for hydrogen, $SC_{rt,H2,j,ir,t}$ is the specific hydrogen consumption in the process unit $j$ and $LevelCap_{rt,j,ir,t}$ is the level capacity of the process unit $j$. $DEM_{rt,H2,UHDT,ir,t}$ is the demand for hydrogen from the UHDT unit[6]. $P_{rt,H2,ir,t}$ is the hydrogen production in refineries, $\alpha_{rt,H2,HGU}$ is the hydrogen yield in hydrogen generation units, $LevelCap_{rt,HGU,ir,t}$ is the level capacity of these units, $\alpha_{rt,H2,CRU}$ is the hydrogen yield in catalytic reforming units and $LevelCap_{rt,CRU,ir,t}$ is the level capacity of these units.

### A.2.5. CO$_2$ emissions

$$CO2Emissions_{rt,ir,t} = X_{rt,NGCOG,ir,t} \cdot EF_{NG} + \sum_{st} X_{rt,st,NGBoiler,ir,t} \cdot EF_{NG} + X_{rt,RG,ir,t} \cdot EF_{RG} + X_{rt,FO,ir,t} \cdot EF_{FO} + X_{rt,CK,ir,t} \cdot EF_{CK} + X_{rt,GE,ir,t} \cdot EF_{GE} + \alpha_{rt,H2,HGU} \cdot LevelCap_{rt,HGU,ir,t} \cdot EF_{H2prod} \tag{A.40}$$

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[6] See Section A.2.9 for its definition.

For a refinery type $rt$, an internal region $ir$ and a period $t$, total $CO_2$ emissions are given by the sum of the amount of fuel or grid electricity consumed multiplied by the respective emission factors, $EF$. Moreover, the amount of hydrogen produced in HGU units, defined by their level capacity, $LevelCap_{rt,HGU,ir,t}$, multiplied by the hydrogen yield, $\alpha_{rt,H2,HGU}$, must also be multiplied by the emission factor related to $CO_2$ emissions in this reaction, $EF_{H2prod}$. This accounts for process emissions in hydrogen production.

### A.2.6. Quality specification of products

The model describes these specifications in terms of linear equations. This means that the sum of the amount of each intermediate product $i$ that composes the pool of a final product multiplied by the evaluated property must be inferior, superior, or in-between required technical specifications.

$$P_{rt,n,ir,t} \cdot \beta_{1,n} \leq \sum_{i,j} O_{rt,j,i,ir,t} \cdot \theta_{i,j} \text{ or}$$
$$\sum_{i,j} O_{rt,j,i,ir,t} \cdot \theta_{i,j} \leq P_{rt,n,ir,t} \cdot \beta_{2,n} \text{ or} \tag{A.41}$$
$$P_{rt,n,ir,t} \cdot \beta_{1,n} \leq \sum_{i,j} O_{rt,j,i,ir,t} \cdot \theta_{i,j} \leq P_{rt,n,ir,t} \cdot \beta_{2,n}$$

For a refinery type $rt$ an internal region $ir$ and a period $t$, $O_{rt,j,i,ir,t}$ is the amount of intermediate product $i$ outputted from the processing unit $j$ which composes the pool of a final product $n$, and $\theta_{i,j}$ is the evaluated property for this intermediate product. $P_{rt,n,ir,t}$ is the amount of final product $n$ and $\beta_{1,n}$ and $\beta_{2,n}$ are required technical specifications for the property.

### A.2.7. Demand for final products

$$\sum_{ir_{ab}} P_{CR,n,ir_{ab},t} + \sum_{ir_{ab}} P_{MR,n,ir_{ab},t} + \sum_e I_{n,e,ir_b,t} \geq \sum_e E_{n,e,ir_b,t} + DEM_{n,ir_b,t} \tag{A.42}$$

For a given product $n$ demanded by a given internal region $ir_b$ in a period $t$, $\sum_{ir_{ab}} P_{CR,n,ir_{ab},t}$ and $\sum_{ir_{ab}} P_{MR,n,ir_{ab},t}$ represent the total amount of internal trade of products coming from conventional and modular mini refineries, respectively. It is important to observe that, when the supply region is the same as the demand region ($a = b$), acquisition from own production by the region is being represented. $\sum_e I_{n,e,ir_b,t}$ represent the total imported amount of product $n$, and $\sum_e E_{n,e,ir_b,t}$ represent its total exported amount. Finally, $DEM_{n,ir_b,t}$ is the demand for the product.

### A.2.8. Constraints on imports and exports

$$\sum_{e,ir} I_{pt,e,ir,t} + \sum_{e,ir} E_{pt,e,ir,t} \leq CapInfra_{pt,t} \tag{A.43}$$

$$CapInfra_{pt,t(\neq to)} = CapInfra_{pt,t-1} + AddCapInfra_{pt,t} \tag{A.44}$$

For given internal regions $ir$ and a given external region $e$ in a period $t$, $I_{pt,e,ir,t}$ and $E_{pt,e,ir,t}$ are the imported and exported amounts of product type $pt$, respectively. As stated in section A.1.11, $pt$ represents one of three categories of oil products, light (LPG, naphtha, and gasoline), medium (kerosene, jet fuel oil, diesel, fuel oil and heating fuel oil) and heavy (petroleum coke). $CapInfra_{pt,t}$ and $CapInfra_{pt,t-1}$ are the infrastructure (e.g., harbor) capacity in periods $t$ and $t-1$, respectively, and $AddCapInfra_{pt,t}$ represents the added capacity in $t$, for $t$ from $t1$ on. It should be noted that $CapInfra_{pt,t0}$ is defined by the user.

### A.2.9. Biomass co-processing

$$P_{biotype,ir,t} + \sum_{ir} I_{biotype,ir,t} - \sum_{ir} E_{biotype,ir,t} \geq \sum_{rt} In_{rt,biotype,UHDT,ir,t} \tag{A.45}$$

$$In_{rt,biotype,UHDT,ir,t} \leq x_{biotype} \cdot LevelCap_{rt,UHDT,ir,t} \tag{A.46}$$

$$\begin{aligned} DEM_{rt,H2,UHDT,ir,t} = {} & SC_{rt,H2,UHDTF,ir,t} \cdot (1 - x_{biotype}) \cdot \\ & LevelCap_{rt,UHDT,ir,t} + SC_{rt,H2,UHDTB,ir,t} \cdot x_{SVO} \cdot LevelCap_{rt,UHDT,ir,t} \end{aligned} \tag{A.47}$$

$$\begin{aligned} OPEX_{rt,UHDT} = {} & \left( \sum_{s,t} \left(1 + \frac{1}{CRF}\right) \cdot \frac{\left(FOM_{rt,UHDTF} + VOM_{rt,UHDTF}\right) \cdot (1 - x_{biotype}) \cdot LevelCap_{rt,UHDT,ir,t}}{(1+r)^{t-t_0}} \right) \\ & + \left( \sum_{s,t} \left(1 + \frac{1}{CRF}\right) \cdot \frac{\left(FOM_{rt,UHDTB} + VOM_{rt,UHDTB}\right) \cdot x_{biotype} \cdot LevelCap_{rt,UHDT,ir,t}}{(1+r)^{t-t_0}} \right) \end{aligned} \tag{A.48}$$

Given an internal region $ir$ and a period $t$, $P_{biotype,ir,t}$ is the biomass oil produced in the region, $\sum_{ir} I_{biotypebio,ir,t}$ represents the biomass oil acquired from other regions, $\sum_{ir} E_{biotype,ir,t}$ corresponds to the biomass oil sent to other regions and $\sum_{rt} In_{rt,biotype,UHDT,ir,t}$ is the amount inputted in the UHDT units for all refinery types $rt$. In addition, $x_{biotype}$ represents the biomass oil mass fraction in the input feed of the UHDT units, and $LevelCap_{rt,UHDT,ir,t}$ represents the level capacity of these units. $DEM_{H2,rt,UHDT,ir,t}$ represents the UHDT demand for hydrogen, while $SC_{rt,H2,UHDTF,ir,t}$ and $SC_{rt,H2,UHDTB,ir,t}$ represent the specific consumptions associated with the operation with fossil and biomass feedstocks, respectively. Similarly, $FOM_{rt,UHDTF}$ and $VOM_{rt,UHDTF}$ correspond to the fixed and variable operating costs associated with this unit when operating with fossil feedstocks, while $FOM_{rt,UHDTB}$ and $VOM_{rt,UHDTB}$ are the costs associated with its operation with biomass as a feedstock.

### A.2.10. Modular mini refineries

$$AddCap_{MR,ADU,ir,t} = N * TypCap_{MR,ADU} \tag{A.49}$$

For a given supply region $ir$ and period $t$, $AddCap_{MR,ADU,ir,t}$ is the additional capacity due to new investments of atmospheric distillation units in modular mini refineries ($MR$). This capacity is equal to the number of units, $N$, multiplied by the typical capacity of this kind of unit, $TypCap_{MR,ADU}$. $N$ is defined in the model as a positive integer variable.

## B. Annex B: Data used in the case study

This Annex presents the main data used in the definition of the case study presented in Section 4, and follows the categories presented in Table 1.

### B.1. Number of regions

Table B.1. Number of internal and external regions.

| | |
|---|---|
| **Number of internal regions** | 4 (South region (S); Rio de Janeiro Minas Gerais and Espírito Santo states (RJ/MG/ES); São Paulo state (SP); North, Northeast and Midwest regions (N/NE/CO)) |
| **Number of external regions** | 6 (United States (USA), Central America (CA), Western Europe (WE), Middle East (ME), Africa (AF) and Asia-Pacific (AP)) |

### B.2. Crude oil definition

Table B.2. Crude oil types, availability, and properties.

| | **Availability (Mt/year)** | **API gravity** | **Sulfur content (%wt)** |
|---|---|---|---|
| **Light** | 10.2 | 58.16 | 0.04 |
| **Medium** | 26.0 | 33.32 | 1.71 |
| **Heavy** | 90.0 | 26.90 | 0.44 |

Source: [23], [24] as cited in [6].

Table B.3. Reference crude oil (Brent) FOB price and growth rates.

| | **Brent Price (base year) and growth rates referenced to the base year (other years)** |
|---|---|
| **2015** | 64.2 $USD_{2015}$/bbl |
| **2020** | 10.8 % |
| **2025** | 21.6 % |
| **2030** | 32.4 % |
| **2035** | 32.4 % |
| **2040** | 32.4 % |

Source: [25], [26].

Table B.4. Crude oil freight prices.

| | **Crude oil freight prices ($USD_{2015}$/bbl)** | | | |
|---|---|---|---|---|
| | **S** | **N/NE/CO** | **RJ/MG/ES** | **SP** |
| **Light** | 3.80 | 3.80 | 3.80 | 3.80 |
| **Medium** | 5.60 | 5.60 | 5.60 | 5.60 |
| **Heavy** | 0.56 | 0.75 | 0.14 | 0.19 |

Source: [11], [12], [27] as cited in [6].

## B.3. Renewable oil definition

Table B.5. Soy SVO availability and growth rates.

| | **Availability (base year) and growth rates referenced to previous period** | | | |
|---|---|---|---|---|
| | **S** | **N/NE/CO** | **RJ/MG/ES** | **SP** |
| **2015** | 0.90 Mt | 1.45 Mt | 0.12 Mt | 0.07 Mt |
| **2020** | 22.3 % | 60.7 % | 47.9 % | 51.2 % |
| **2025** | -20.0 % | -8.75 % | -20.0 % | -20.0 % |
| **2030** | -12.5 % | -23.3 % | -12.5 % | -12.5 % |
| **2035** | 0 | 0 | 0 | 0 |
| **2040** | 0 | 0 | 0 | 0 |

Source: [28], [29].

Table B.6. Reference soy SVO price and growth rates.

| | **Price (base year) and growth rates referenced to previous period (other years)** |
|---|---|
| **2015** | 900 ($USD_{2015}$/t) |
| **2020** | 5.6 % |
| **2025** | 5.3 % |
| **2030** | - |
| **2035** | - |
| **2040** | - |

Source: [30], [31].

Table B.7. Soy SVO internal freight prices.

| | Internal freight prices ($USD_{2015}$/t)[1] | | | |
|---|---|---|---|---|
| | **S** | **N/NE/CO** | **RJ/MG/ES** | **SP** |
| **S** | 0 | 18 | 8 | 4.7 |
| **N/NE/CO** | 18 | 0 | 10.7 | 13.3 |
| **RJ/MG/ES** | 8 | 10.7 | 0 | 2.7 |
| **SP** | 4.7 | 13.3 | 2.7 | 0 |
| [1]Considered the same as for refining products. | | | | |

Source: [27] as cited in [6].

Table B.8. Maximum SVO in the UHDT unit feed.

| | |
|---|---|
| **Maximum SVO in the UHDT feed (wt%)** | 25 |

## B.4. Refining operations definition

Table B.9. Process units' capacities in the base year.

| | Base year capacities (Mt/year)[1] | | | |
|---|---|---|---|---|
| | **S** | **N/NE/CO** | **RJ/MG/ES** | **SP** |
| **ADU** | 22.4 | 25.8 | 21.4 | 47.2 |
| **VDU** | 7.3 | 7.0 | 11.0 | 21.3 |
| **DSP** | 1.7 | 0.0 | 2.3 | 2.3 |
| **NHDT** | 0.0 | 0.1 | 0.4 | 4.0 |
| **CRU** | 0.3 | 0.3 | 0.6 | 2.3 |
| **KHDT** | 0.0 | 0.0 | 1.8 | 2.0 |
| **DHDT** | 7.0 | 5.5 | 5.9 | 12.2 |
| **FCC** | 4.8 | 2.2 | 4.7 | 13.2 |
| **RFCC** | 2.4 | 4.6 | 0.0 | 1.0 |
| **HCK** | 0.0 | 0.0 | 0.0 | 0.0 |
| **GHDS** | 4.7 | 4.8 | 4.5 | 7.2 |
| **ALK** | 0.0 | 0.0 | 0.0 | 0.3 |
| **COK** | 2.5 | 3.9 | 2.9 | 7.2 |
| **UHDT** | 2.8 | 3.0 | 2.7 | 6.1 |
| **HGU** | 1,376.3 | 1,785.0 | 1,521.4 | 3,300.0 |
| **COG** | 103.9 | 68.9 | 120.5 | 217.2 |
| [1]Except for HGU: $MNm^3$/year and COG: MW | | | | |

Source: [32], [33] as cited in [6].

Table B.10. Refining costs.

| | **CAPEX (USD$_{2015}$/(t/year))**[1,2] | **OPEX (USD$_{2015}$/t)**[3,4] |
|---|---|---|
| **ADU** | 74.4 | 3.0 |
| **VDU** | 41.7 | 1.7 |
| **DSP** | 61.8 | 2.5 |
| **NHDT** | 56.6 | 2.3 |
| **CRU** | 114.4 | 4.6 |
| **KHDT** | 56.6 | 2.3 |
| **DHDT** | 56.6 | 2.3 |
| **FCC** | 189.4 | 7.6 |
| **RFCC** | 189.4 | 7.6 |
| **HCK** | 253.0 | 10.1 |
| **GHDS** | 83.3 | 3.3 |
| **ALK** | 446.4 | 17.9 |
| **COK** | 208.3 | 8.3 |
| **UHDT, F**[5] | 142.9 | 5.7 |
| **UHDT, S**[6] | 142.9 | 6.3 |
| **HGU** | 0.19 | 0.01 |
| **COG** | 1.94 | 0.08 |

[1] ISBL = OSBL, ISBL+OSBL = CAPEX

[2] Except for HGU: USD/(Nm$^3$/year) and COG: 10$^6$ USD/MW

[3] FOM=VOM, FOM+VOM = OPEX

[4] Except for HGU: USD/Nm$^3$ and COG: 10$^6$ USD/MWyear

[5] Data related to the UHDT unit when operating with fossil feedstock.

[6] Data related to the UHDT unit when operating with SVO as feedstock.

Source: [12], [34] as cited in [6].

Table B.11. Yields of the ADU.

| | **Diesel campaign (mass basis) (%)** | | | **Naphtha campaign (mass basis) (%)** | | |
|---|---|---|---|---|---|---|
| | **Light** | **Medium** | **Heavy** | **Light** | **Medium** | **Heavy** |
| **Refinery gas** | 0.04 | 0.06 | 0.03 | 0.04 | 0.06 | 0.03 |
| **LPG** | 3.00 | 1.83 | 0.27 | 3.00 | 2.00 | 1.50 |
| **LSRN** | 11.96 | 5.00 | 3.00 | 17.00 | 12.00 | 9.00 |
| **HSRN** | 11.00 | 5.00 | 3.00 | 14.80 | 11.94 | 10.00 |
| **Kerosene** | 4.00 | 2.00 | 1.00 | 5.00 | 4.00 | 3.00 |
| **Diesel** | 32.00 | 34.00 | 36.73 | 28.00 | 30.00 | 34.03 |
| **AGO** | 21.00 | 25.00 | 26.00 | 17.16 | 18.00 | 16.50 |
| **ATR** | 17.00 | 27.11 | 29.97 | 15.00 | 22.00 | 25.94 |

Source: [23], [24], [35], [36] as cited in [6].

Table B.12. Yields of the VDU.

| | **Yields (mass basis) (%)** | | |
|---|---|---|---|
| **Product** | **Light** | **Medium** | **Heavy** |
| **LVGO** | 37.57 | 17.68 | 30.10 |
| **HVGO** | 18.78 | 26.22 | 34.95 |
| **Vacuum Residue** | 43.65 | 56.10 | 34.95 |

Source: [23], [24], [35], [36] as cited in [6].

Table B.13. Yields of other units.

| | Yields (mass basis) (%) | | | | | |
|---|---|---|---|---|---|---|
| | **FCC** | **RFCC** | **HCK** | **ALK** | **CRU** | **COK** |
| **Refinery Gas** | 3.0 | 3.0 | 0.4 | - | - | 5.0 |
| **LPG** | 14.0 | 17.0 | 3.8 | 17.0 | 15.0 | 4.0 |
| **Naphtha** | - | - | - | - | - | 7.0 |
| **Gasoline** | 50.0 | 45.0 | 20.0 | 83.0 | 85.0 | |
| **Kerosene** | - | - | 25.0 | - | - | - |
| **Diesel** | - | - | 37.0 | - | - | - |
| **Light cycle oil** | 17.0 | 18.0 | - | - | - | - |
| **Light gasoil** | - | - | - | - | - | 40.0 |
| **Heavy gasoil** | - | - | - | - | - | 14.0 |
| **Slurry oil** | 12.0 | 13.0 | 13.8 | - | - | - |
| **Coke** | 4.0 | 4.0 | - | - | - | - |

Source: [23], [24], [35], [36] as cited in [6].

Table B.14. Specific consumption of utilities.

| | HP Steam (MJ/t) | MP Steam (MJ/t) | LP Steam (MJ/t) | Electricity (kWh/t) | Fuel (MJ/t) | $H_2$ (Nm$^3$/t) |
|---|---|---|---|---|---|---|
| **ADU** | | 222.7 | | 4.4 | 933.8 | |
| **VDU** | | 167 | | 7 | 636.8 | |
| **DSP** | | | 79.37 | 14.71 | 772.06 | |
| **FCC** | -328.8 | 404.8 | -71.4 | 64.7 | 2705.9 | |
| **RFCC** | -369.9 | | | 7.4 | 2705.9 | |
| **ALK** | | 1821.9 | | 22.1 | 1161.8 | |
| **CRU** | -320.6 | | | 73.5 | 2808.8 | -352.9 |
| **COK** | | -372.5 | | 26.5 | 926.5 | |
| **GHDS** | 61.7 | | | 14.7 | 772.1 | 29.41 |
| **NHDT** | 61.7 | | | 14.7 | 772.1 | 51.47 |
| **KHDT** | 82.2 | | | 22.1 | 1161.8 | 125 |
| **DHDT** | 82.2 | | | 22.1 | 1161.8 | 250 |
| **UHDT, F**[1] | 102.8 | | | 44.1 | 1551.5 | 310.7 |
| **UHDT, S**[2] | 102.8 | | | 44.1 | 1551.5 | 714.6 |
| **HGU** | -0.08 | - | - | 8.09 | 18.4 | -1.47 |

[1] Data related to the UHDT unit when operating with fossil feedstock.

[2] Data related to the UHDT unit when operating with SVO as feedstock.

Source: [35], [36], [37], [38] as cited in [6].

Table B.15. Prices of fuels and electricity.

| Fuel/Electricity | Price |
|---|---|
| Natural gas (USD/MMBtu) | 14.2 |
| Electricity (USD/kWh) | 0.2 |

Source: [39], [40].

Table B.16. $CO_2$ emission factors.

| **Fuel/Electricity/Process** | **Emission Factor** |
|---|---|
| Natural gas ($tCO_2/TJ$) | 56.1 |
| Refinery gas ($tCO_2/TJ$) | 57.6 |
| Fuel Oil ($tCO_2/TJ$) | 77.4 |
| Coke ($tCO_2/TJ$) | 97.5 |
| Electricity ($tCO_2/MWh$) | 0.1244 |
| Hydrogen production from natural gas (tCO2/tH2) | 5.0 |

Source: [41], [42] as cited in [6].

Table B.17. CO2 taxation price.

| **$CO_2$ taxation price** | Not used in this example |
|---|---|

## B.5. Modular mini refineries definition

Table B.18. Process units' capacities in the base year.

| | **Base year capacities (Mt/year)**[1] | | | |
|---|---|---|---|---|
| | **S** | **N/NE/CO** | **RJ/MG/ES** | **SP** |
| **ADU** | 0.0 | 0.0 | 0.0 | 0.0 |
| **VDU** | 0.0 | 0.0 | 0.0 | 0.0 |
| **NHDT** | 0.0 | 0.0 | 0.0 | 0.0 |
| **CRU** | 0.0 | 0.0 | 0.0 | 0.0 |
| **KHDT** | 0.0 | 0.0 | 0.0 | 0.0 |
| **DHDT** | 0.0 | 0.0 | 0.0 | 0.0 |
| **FCC** | 0.0 | 0.0 | 0.0 | 0.0 |
| **GHDS** | 0.0 | 0.0 | 0.0 | 0.0 |
| **UHDT** | 0.0 | 0.0 | 0.0 | 0.0 |
| **HGU** | 0.0 | 0.0 | 0.0 | 0.0 |
| **COG** | 0.0 | 0.0 | 0.0 | 0.0 |

[1] Except for HGU: $MNm^3$/year and COG: MW

Table B.19. Typical small-scale ADU capacity.

| **Typical small-scale ADU capacity (Mt/year)** | 1.0 |
|---|---|

Source: [10].

Table B.20. Refining costs.

| | **CAPEX (USD$_{2015}$/(t/year))**[1,2,3] | **OPEX (USD$_{2015}$/t)**[4,5] |
|---|---|---|
| **ADU** | 17.9 | 0.72 |
| **VDU** | 12.4 | 0.50 |
| **NHDT** | 26.8 | 1.08 |
| **CRU** | 69 | 2.76 |
| **KHDT** | 33.8 | 1.36 |
| **DHDT** | 33.8 | 1.36 |
| **FCC** | 55.8 | 2.24 |
| **GHDS** | 50.8 | 2.04 |
| **UHDT** | 85.8 | 3.44 |
| **HGU** | 0.1 | 0.004 |
| **COG** | 1.0 | 0.04 |

[1] ISBL = OSBL, ISBL+OSBL = CAPEX
[2] Except for HGU: USD/(Nm$^3$/year) and COG: 10$^6$ USD/MW
[3] Costs estimated using a scale factor law and the costs of large-scale units.
[4] FOM=VOM, FOM+VOM = OPEX
[5] Except for HGU: USD/Nm$^3$ and COG: 10$^6$ USD/MWyear

## B.6. Intermediate products definition

Table B.21. Properties of streams that compose the gasoline pool.

| **Streams to gasoline pool** | **Sulfur content (%wt)** | **Density (kg/m$^3$)**[1] | **Octane number**[1] |
|---|---|---|---|
| GHDS Gasoline | 0.005 | 761 – 762.2 | 111.6 – 111.7 |
| GHDS Bypass | 0.009 | 750.2 | 111.3 |
| CRU Gasoline | 0.005 | 796.2 – 809.1 | 105.1 – 106.8 |
| CRU Bypass | 0.005 | 746.3 – 786.2 | 89.2 – 93.8 |

[1] The use of value ranges occurs when different types of crude oil lead to different values of the property.

Source: [11], [12].

Table B.22. Properties of streams that compose the kerosene pool.

| **Streams to kerosene pool** | **Sulfur content (%wt)**[1] |
|---|---|
| KHDT Kerosene | 0.001 |
| KHDT Bypass | 0.02 – 0.7 |
| HCK Kerosene | 0.03 |

[1] The use of value ranges occurs when different types of crude oil lead to different values of the property.

Source: [11], [12].

Table B.23. Properties of streams that compose the jet fuel pool.

| **Streams to jet fuel pool** | **Sulfur content (%wt)**[1] |
|---|---|
| KHDT Kerosene | 0.001 |
| KHDT Bypass | 0.02 – 0.7 |
| HCC Kerosene | 0.03 |

[1] The use of value ranges occurs when different types of crude oil lead to different values of the property.

Source: [11], [12].

Table B.24. Properties of streams that compose the diesel pool.

| **Streams to diesel pool** | **Sulfur content (%wt)**[1] | **Density (kg/m$^3$)**[1] | **Cetane number**[1] |
|---|---|---|---|
| KHDT Kerosene | 0.001 | 775.2 – 815.7 | 53.9 – 55.5 |
| KHDT Bypass | 0.02 – 0.74 | 791.1 – 831.9 | 53.9 – 55.5 |
| DHDT Diesel | 0.001 | 817 – 834.7 | 61.6 - 64 |
| DHDT Bypass | 0.03 – 3.59 | 841 – 874.1 | 59.3 – 62.8 |
| HCC Diesel | 0.03 | 818.3 – 831.3 | 73.9 |
| UHDT Diesel | 0.001 | 859.8 | 64 – 67.5 |
| FCC LCO | 0.4 – 2.9 | 874.9 – 887.3 | 20.4 – 20.6 |
| RFCC LCO | 0.4 – 2.9 | 874.9 – 887.3 | 20.4 – 20.6 |
| UHDT HVO | 0.00035 | 851.8 | 96.2 |

[1] The use of value ranges occurs when different types of crude oil lead to different values of the property.

Source: [11], [12].

Table B.25. Properties of streams that compose the fuel oil pool.

| **Streams to fuel oil pool** | **Sulfur content (%wt)**[1] |
|---|---|
| UHDT Fuel Oil | 0.5 |
| UHDT Bypass | 0.6 – 1 |

[1] The use of value ranges occurs when different types of crude oil lead to different values of the property.

Source: [11], [12].

## B.7. Final products definition

Table B.26. Required properties for final products.

| | **Maximum sulfur content (%wt)** | **Density range (kg/m$^3$)** | **Minimum octane number** | **Minimum cetane number** |
|---|---|---|---|---|
| **Gasoline** | 0.005 | 689 – 775 | 85 | |
| **Kerosene** | 0.06 | - | - | |
| **Jet fuel** | 0.06 | - | - | |
| **Diesel** | 0.001 | 815 - 850 | - | 48 |
| **Fuel oil** | 3.5 | - | - | |

Source: [43] as cited in [6].

Table B.27. Demand for products in the base year.

| | Demand for products in the base year (Mt/year) | | | |
|---|---|---|---|---|
| | **S** | **N/NE/CO** | **RJ/MG/ES** | **SP** |
| **LPG** | 1.35 | 2.90 | 1.35 | 1.87 |
| **Naphtha** | 1.95 | 3.38 | 1.56 | 2.08 |
| **Gasoline** | 4.84 | 8.39 | 3.93 | 5.29 |
| **Kerosene** | 0.0004 | 0.0019 | 0.0013 | 0.0025 |
| **Jet Fuel** | 0.41 | 1.83 | 1.22 | 2.44 |
| **Diesel** | 9.66 | 10.86 | 7.38 | 18.78 |
| **Fuel Oil** | 2.62 | 3.03 | 2.48 | 5.51 |
| **Heating Fuel Oil** | 0.30 | 0.30 | 0.30 | 0.61 |
| **Coke** | 0.90 | 1.91 | 0.90 | 1.20 |

Source: [21], [22] as cited in [6].

Table B.28. Demand for products growth rates.

| | Demand for products growth rates based on previous period (%) | | | | |
|---|---|---|---|---|---|
| | **2020** | **2025** | **2030** | **2035** | **2040** |
| **LPG** | -1.88 | -5.87 | -15.24 | -6.85 | -8.09 |
| **Naphtha** | 12.14 | 14.0 | 10.02 | 9.82 | 9.08 |
| **Gasoline** | -1.96 | -5.77 | -15.28 | -6.83 | -8.06 |
| **Kerosene** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Jet Fuel** | -8.15 | -8.87 | -9.53 | -10.76 | -12.06 |
| **Diesel** | 4.26 | -12.76 | -33.52 | -13.71 | -16.10 |
| **Fuel Oil** | 4.99 | -17.25 | -4.81 | -5.32 | -4.68 |
| **Heating Fuel Oil** | 4.61 | -16.98 | -5.30 | -4.80 | -5.04 |
| **Coke** | 4.27 | -4.48 | -3.06 | -3.16 | -5.22 |

Source: [21], [22] as cited in [6].

Table B.29. Final products internal freight prices.

| | Internal freight prices ($USD_{2015}$/t)[1] | | | |
|---|---|---|---|---|
| | **S** | **N/NE/CO** | **RJ/MG/ES** | **SP** |
| **S** | 0 | 18 | 8 | 4.7 |
| **N/NE/CO** | 18 | 0 | 10.7 | 13.3 |
| **RJ/MG/ES** | 8 | 10.7 | 0 | 2.7 |
| **SP** | 4.7 | 13.3 | 2.7 | 0 |

[1] To simplify the calculation of national freight, only the pipeline modal was taken into account, despite the existence of other transportation modes in Brazil. Additionally, the freight cost was kept constant for all petroleum products.

Source: [27] as cited in [6].

Table B.30. Final products FOB import/export prices in the base year and growth rates.

| | | **Growth rates based on previous period (%)** | | | | |
|---|---|---|---|---|---|---|
| | **FOB import/export prices for final products in the base year (USD$_{2015}$/year)** | **2020** | **2025** | **2030** | **2035** | **2040** |
| **LPG** | 214.79 | 11 | 64 | 71 | 76 | 79 |
| **Naphtha** | 451.67 | 11 | 61 | 70 | 79 | 97 |
| **Gasoline** | 528.67 | 11 | 64 | 71 | 76 | 79 |
| **Kerosene** | 506.92 | 6 | 30 | 37 | 44 | 47 |
| **Jet Fuel** | 506.92 | 10 | 51 | 59 | 70 | 71 |
| **Diesel** | 493.48 | 6 | 30 | 37 | 44 | 47 |
| **Fuel Oil** | 431.33 | 16 | 73 | 85 | 100 | 103 |
| **Heating Fuel Oil** | 431.33 | 6 | 48 | 57 | 68 | 70 |
| **Coke** | 56.08 | 16 | 73 | 85 | 100 | 103 |

Source: [44], [45] as cited in [6].

Table B.31. Final products import freight prices.

| | **Import freight prices (USD$_{2015}$/t)$^1$** | | | | | |
|---|---|---|---|---|---|---|
| | **USA** | **CA** | **WE** | **AF** | **ME** | **AP** |
| **All products** | 20.05 | 20.05 | 33.45 | 25.62 | 40.47 | 45.37 |

[1] Shipping costs from the oversea regions of the model to the internal regions. To simplify, the costs of an oversea region are the same, regardless of the Brazilian demand region.

Source: [12] as cited in [6].

Table B.32. Information on infrastructure for final products transport.

| | **Installed capacity – base year (Mt/year)** | **Expansion costs (USD$_{2015}$/(t/year))** |
|---|---|---|
| **Light products** | 11.5 | 65 |
| **Medium products** | 24 | 65 |
| **Heavy products** | 7.5 | 65 |

Source: [32], [46], [47] as cited in [6].

## B.8. Economic settings

Table B.33. Discount rate.

| | |
|---|---|
| **Discount rate (%)** | 10 |

Source: [48] as cited in [6].

# C. Annex C: List of variables and subscripts

## C.1. List of variables

$AddCap$: additional capacity of a process unit

$AddCapInfra$: additional capacity of infrastructure for external trade

$Av$: feedstock availability

$BoilerEff$: efficiency of boilers for steam production

$Cap$: available capacity of a process unit

$CAPEX$: capital expenditures

$CAPEXINFRA$: capital expenditures of structures that enable external trade

$CapInfra$: available capacity of infrastructure for external trade

$CF$: capacity factor of a process unit

$CO2C$: $CO_2$ emissions costs

$CO2Emissions$: amount of $CO_2$ emissions in refineries

$COGElecEff$: efficiency of cogeneration for electricity production

$COGSteamEff$: efficiency of cogeneration for steam production

$CostAddInfra$: cost of additional infrastructure for external trade

$CRF$: capital recovery factor

$Dem$: demand for a utility or a final product

$E$: exported amount of a feedstock or a final product

$EF$: emission factor

$ElecCOG$: amount of electricity produced by cogeneration

$ElecGrid$: amount of electricity purchased from the grid

$EPC$: electricity purchase costs

$Exc$: excess amount of a utility

$EXP$: revenues with exports of final products

$FOBPrice$: free-on-board price of a product

$FOM$: fixed operating costs

$FPC$: fuel purchase costs

$FreightPrice$: price of transporting a feedstock or product between regions

$I$: imported amount of a feedstock or a final product

$IMP$: costs to import final products

$In$: amount inputted in a process unit

$INTTRAD$: costs related to internal trade of final products

$ISBL$: inside battery limits costs

$LevelCap$: capacity level of a process unit

$N$: number of atmospheric distillation units in modular mini refineries

$NomCap$: nominal capacity of a process unit

$O$: amount outputted from a process unit

$OPC$: oil purchase costs

$OPEX$: operating expenditures

$OSBL$: outside battery limits costs

$P$: amount produced of a feedstock, a utility, or a final product

$Price$: price of a feedstock or utility

$PriceCO2$: price of $CO_2$ emissions

$r$: discount rate

$SC$: specific consumption of a utility in a process unit

$SteamBoilers$: amount of steam produced by boilers

$SteamCOG$: amount of steam produced by cogeneration

$BIOPC$: straight vegetable oil purchase costs

$t$: periods of time

$TurbineEff$: efficiency of turbines

$TypCap$: typical capacity of units

$VOM$: variable operating costs

$x$: mass fraction

$X$: amount consumed of a feedstock or a utility

$Z$: objective function

$\alpha$: product yield

$\beta$: technical specifications for properties of final products

$\Delta\ ^{o}API$: difference of API gravity between two types of oil

$\Delta Sulfur$: difference of sulfur content between two types of oil

$\theta$: properties of intermediate products

### C.2. List of subscripts

$biotype$: biomass oil type (SVO, UCO, animal fats etc.)

$CK$: coke

$CR$: conventional large-scale refineries
$CRU$: catalytic reforming unit
$Elec$: electricity
$er$: external regions
$FO$: fuel oil
$Fuel$: fuel
$GE$: grid electricity
$H2$: hydrogen
$HGU$: hydrogen generation unit
$HP$: high-pressure steam
$i$: intermediate products
$ir$: internal regions
$j$: process units
$k$: input feeds
$LP$: low-pressure steam
$MP$: medium-pressure steam
$MR$: modular mini refineries
$n$: final products
$NG$: natural gas
$NGBoiler$: natural gas used in boilers
$NGCOG$: natural gas used in cogeneration
$NGHGU$: natural gas used in hydrogen generation units
$oiltype$: crude oil type (light, medium or heavy)
$pt$: product type (light, medium or heavy)
$ref$: reference crude oil
$RG$: refinery gas
$rt$: refinery type ($CR$ or $MR$)
$st$: steam type ($HP, MP\ or\ LP$)
$t$: periods of time
$UHDT$: hydrotreating unit for unstable products
$UHDTB$: hydrotreating unit for unstable products operating with biomass feedstocks
$UHDTF$: hydrotreating unit for unstable products operating with fossil feedstocks

## References

[1] IEA, “France Oil Security Policy,” Oil Security Policy. Accessed: Feb. 01, 2024. [Online]. Available: https://www.iea.org/articles/france-oil-security-policy

[2] IEA, “Transformation,” Key World Energy Statistics. Accessed: Feb. 01, 2024. [Online]. Available: https://www.iea.org/reports/key-world-energy-statistics-2020/transformation

[3] IPCC, *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, NY, USA: Cambridge University Press, 2022. doi: 10.1017/9781009157926.

[4] IRENA, “Stranded Assets and Renewables: How the energy transition affects the value of energy reserves, buildings and capital stock,” Abu Dhabi, 2017. [Online]. Available: www.irena.org/remap

[5] C. Bergman-Fonte *et al.*, “Repurposing, co-processing and greenhouse gas mitigation – The Brazilian refining sector under deep decarbonization scenarios: A case study using integrated assessment modeling,” *Energy*, vol. 282, p. 128435, 2023, doi: https://doi.org/10.1016/j.energy.2023.128435.

[6] F. P. D. C. Guedes, “A multi-regional optimization model for the Brazilian oil refining industry,” Universidade Federal do Rio de Janeiro, 2019.

[7] C. Li, X. He, B. Chen, B. Chen, Z. Gong, and L. Quan, “Integrative optimization of refining and petrochemical plants,” in *16th European Symposium on Computer Aided Process Engineering and 9th International Symposium on Process Systems Engineering*, vol. 21, W. Marquardt and C. B. T.-C. A. C. E. Pantelides, Eds., Elsevier, 2006, pp. 2039–2044. doi: https://doi.org/10.1016/S1570-7946(06)80348-2.

[8] G. L. Gomes, “Análise da integração refino-petroquímica - Oportunidades econômicas, estratégicas e ambientais,” Universidade Federal do Rio de Janeiro, 2011.

[9] E. Ketabchi, E. Mechleri, S. Gu, and H. Arellano-Garcia, “Modelling and Optimisation Approach of an Integrated Oil Refinery and a Petrochemical Plant,” in *13 International Symposium on Process Systems Engineering (PSE 2018)*, vol. 44, M. R. Eden, M. G. Ierapetritou, and G. P. B. T.-C. A. C. E. Towler, Eds., Elsevier, 2018, pp. 1081–1086. doi: https://doi.org/10.1016/B978-0-444-64241-7.50175-0.

[10] R. C. Teixeira, A. S. Szklo, and D. C. Branco, “Adding flexibility to petroleum refining through the introduction of modular plants – a case study for Brazil,” *Energy Sources, Part B Econ. Planning, Policy*, vol. 16, no. 7, pp. 617–637, Jul. 2021, doi: 10.1080/15567249.2021.1952495.

[11] F. Lantz, J. F. Gruson, and V. Saint-Antonin, “Development of a model of the world refining for the POLES model: the OURSE model,” 2005.

[12] F. Lantz, V. Saint-antonin, J. Gruson, W. Suwala, and E. B. Saveyn, *The OURSE model : Simulating the World Refining Sector to 2030*. 2012. doi: 10.2791/73210.

[13] NREL, “Refinery Co-processing Models (RCPM),” Bioenergy Models. Accessed: Nov. 05, 2022. [Online]. Available: https://bioenergymodels.nrel.gov/models/18/

[14] F. Guedes, A. Szklo, P. Rochedo, F. Lantz, L. Magalar, and E. M. V. Arroyo, “Climate-energy-water nexus in Brazilian oil refineries,” *Int. J. Greenh. Gas Control*, vol. 90, no. September 2018, p. 102815, 2019, doi: 10.1016/j.ijggc.2019.102815.

[15] E. Müller-Casseres *et al.*, “Are there synergies in the decarbonization of aviation and shipping? An integrated perspective for the case of Brazil,” *iScience*, 2022, doi: https://doi.org/10.1016/j.isci.2022.105248.

[16] M. Al-Sabawi, J. Chen, and S. Ng, “Hydroprocessing of Biomass-Derived Oils and Their Blends with Petroleum Feedstocks: A Review,” *Energy and Fuels*, vol. 26, no. 9, pp. 5355–5372, 2012, doi: 10.1021/ef3006417.

[17] É. Yáñez, H. Meerman, A. Ramírez, É. Castillo, and A. Faaij, “Assessing bio-oil co-processing routes as CO2 mitigation strategies in oil refineries,” *Biofuels, Bioprod. Biorefining*, vol. 15, no. 1, pp. 305–333, 2021, doi: 10.1002/bbb.2163.

[18] S. van Dyk, J. Su, J. D. McMillan, and J. (John) N. Saddler, “‘Drop-in’ Biofuels: the key role that co-processing will play in its production,” 2019.

[19] IEA, “Oil 2021 - Analysis and forecast to 2026,” 2021.

[20] A. S. Szklo, V. C. Uller, and M. H. P. Bonfá, *Fundamentos do Refino de Petróleo: Tecnologia e Economia*, 3a edição. Rio de Janeiro, 2012.

[21] IEA, “World Energy Outlook 2018,” 2018.

[22] EPE, “Plano Decenal de Expansão de Energia,” Rio de Janeiro, 2020.

[23] M. M. de Barros and A. Szklo, “Petroleum refining flexibility and cost to address the risk of ethanol supply disruptions: The case of Brazil,” *Renew. Energy*, vol. 77, pp. 20–31, 2015, doi: https://doi.org/10.1016/j.renene.2014.11.081.

[24] Bergerson, J., Abella, J. P., Motazedi, K., Guo, J., and K. Cousart, “Petroleum Refinery Life Cycle Inventory Model (PRELIM) - PRELIM v1.2- User guide and technical documentation,” University of Calgary, 2017.

[25] FRED, “Commodities prices,” FRED Economic Data. Accessed: Feb. 11, 2021. [Online]. Available: https://fred.stlouisfed.org/series/WRGASLA#0

[26] IEA, “World Energy Outlook,” World Energy Outlook. Accessed: Feb. 01, 2024. [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2023

[27] J. M. Ferreira Coelho and A. Szklo, “Dealing with petroleum surpluses in Brazil through optimization refining model,” *Energy Strateg. Rev.*, vol. 6, pp. 80–91, 2015, doi: 10.1016/j.esr.2015.04.001.

[28] CONAB, “Acompanhamento da Safra Brasileira,” 2023. [Online]. Available: https://www.conab.gov.br/info-agro/safras/cana

[29] IAMC, “BLUES - Model Documentation,” IAMC Wiki. Accessed: Oct. 13, 2022. [Online]. Available: https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_BLUES

[30] Commodity3, “BRAZIL Fob Paranagua,” SOYOIL. Accessed: Nov. 01, 2023. [Online]. Available: https://www.commodity3.com/chain/SBO0BR/soybean-oil-brazil-fob

[31] OECD, “Agriculture Statistics,” Statistics. Accessed: Nov. 01, 2023. [Online]. Available: https://www.oecd-ilibrary.org/agriculture-and-food/data/oecd-agriculture-statistics_agr-data-en

[32] ANP, “Anuário Estatístico Brasileiro do Petróloeo, Gás Natural e Biocombustíveis,” 2018.

[33] ANEEL, “Banco de Informações de Geração.”

[34] P. R. R. Rochedo, “Development of a global integrated energy model to evaluate the Brazilian role in climate change mitigation scenarios,” Universidade Federal do Rio de Janeiro, 2016.

[35] R. A. Meyers, *Handbook of Petroleum Refining Processes*, vol. 4, no. 1. McGraw-Hill Handbooks, 2004.

[36] J. H. Gary and G. E. Handwerk, *Petroleum Refining: Technology and Economics*. Golden, Colorado, USA: Marcel Dekker, Inc, 2001. doi: 10.1016/0009-2509(94)87025-x.

[37] Hydrocarbon Processing, “Refining Processes Handbook,” Gulf Publishing Company, 2008.

[38] A. Stanislaus, A. Marafi, and M. S. Rana, “Recent advances in the science and technology of ultra low sulfur diesel (ULSD) production,” *Catal. Today*, vol. 153, no. 1, pp. 1–68, 2010, doi: https://doi.org/10.1016/j.cattod.2010.05.011.

[39] ANEEL, “Tarifas ANEEL.” [Online]. Available: https://www.gov.br/aneel/pt-br/assuntos/tarifas

[40] MME, “Boletim mensal de acompanhamento da indústria de gás natural,” Brasília, 2020.

[41] MCTIC, “Fatores de Emissão de CO2 pela geração de energia elétrica no Sistema Interligado Nacional do Brasil - Ano Base 2015. Arquivos dos Fatores de Emissão da Margem de Operação pelo Método da Análise de Despacho. Método da análise de despacho.,” 2018.

[42] IPCC, “2006 IPCC Guidelines for National Greenhouse Gas Inventories,” 2006.

[43] ANP, “Boletim de monitoramento da qualidade dos combustíveis. Publicação mensal – Circulação interna e externa,” 2018.

[44] ARGUS, “Prices & Data,” Argus Media. [Online]. Available: https://www.argusmedia.com/en/

[45] Oil and Gas Journal, “Refined products prices.” [Online]. Available: https://www.ogj.com/

[46] R. Schaeffer *et al.*, “Modelagem setorial de opções de baixo carbono para o setor de óleo e gás natural,” Brasilia, Brasil, 2017.

[47] Secretaria de Portos, “Relatório de metodologias - Plano Nacional de Logística Portuária, Secretaria de Portos,” 2015.

[48] L. P. N. de Oliveira, “Temporal Issues in Mitigation Alternatives for the Energy Sector

in Brazil,” Universidade Federal do Rio de Janeiro, 2016.

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