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Energy consumption and atmospheric emissions from refined petroleum in Mexico by 2030

Consumo de energía y emisiones atmosféricas por el petróleo refinado en México para el año 2030

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Abstract

One of the basic needs for a country's economic development is to cover the major fuel demand, and both energy consumption and environmental impacts resulting from the production of such fuels need to be fast and reliable. The purpose of this paper is to contribute to an estimate of energy consumption and atmospheric emissions of some of the pollutant species reported by Pemex Refinacion under different projections. The predictive estimate model was applied considering four different gasoline demand scenarios, as well as different refining technology options to satisfy fuel consumption needs, based on production yields: four different types of refineries, three types of crude oils and eight different processes. Emission estimates were determined applying emission factors, both for the type of fossil fuel energy source used in the direct heating processes for vapor generation, as well by using electric energy. Results show that the equivalent energy consumption relative to the total processes crude is greater in complex refineries (full conversion); however, a greater conversion efficiency allows a smaller volume of crude consumption needed to satisfy the fuel demand with lower emissions relative to other types of technologies. Mexico's possible refineries need to adapt themselves to different operation scenarios, such as changes in the crude's yield, the quality of the product, variations in the prices of the crude and of the refined products. Therefore, is important to develop and apply perspectives than maximize productivity and minimize energy consumption, reducing air emissions, in constant change scenarios. Finally, the problem would then be evaluating which would be more convenient to obtain a greater socio-economic benefit: reduce emissions to the atmosphere or to lower operation costs of the refinery.
Keywords: Energy consumption, oil refineries, energy efficiency, air pollution, gasolines.

Resumen

Cubrir la demanda de combustibles de mayor consumo es una de las necesidades básicas para el desarrollo económico de un país. Así también, el consumo de energía y los impactos ambientales debidos a la producción de estos combustibles deben ser informados con prontitud y confiabilidad. El objetivo que se persigue en este artículo es contribuir para obtener un estimado del consumo de energía y de las emisiones atmosféricas de algunas de las especies contaminantes reportadas por Pemex refinación, analizando diferentes proyecciones. El modelo de estimación predictivo se aplicó considerando cuatro escenarios de demanda de gasolinas, así como las siguientes opciones tecnológicas de refinación para satisfacer el consumo del combustible, con base en un rendimiento de producción: cuatro tipos de refinerías, tres tipos de crudo y ocho procesos. La estimación de las emisiones se determinó aplicando factores de emisión, tanto por tipo de fuente de energía fósil consumida en los procesos de calentamiento directo o para la generación de vapor, así como por el uso de energía eléctrica. Los resultados muestran que el consumo equivalente de energía respecto al total de crudo procesado es mayor en las refinerías muy complejas (R4), sin embargo, su gran eficiencia de conversión permite consumir menor volumen de crudo para satisfacer la demanda del combustible con emisiones bajas al aire, respecto a otro tipo de tecnologías. Las posibles refinerías en México tendrán que adaptarse a diferentes escenarios operativos, como cambios en el rendimiento del crudo, calidad del producto, así como variación en los precios del crudo y de los productos refinados. Por lo tanto, es importante desarrollar e implementar enfoques que maximicen la productividad y minimicen el consumo de energía, reduciendo las emisiones atmosféricas en escenarios operativos de constante cambio. Por último, el problema sería entonces evaluar qué sería más conveniente para obtener un mayor beneficio socioeconómico: reducir las emisiones a la atmósfera o disminuir los costos de operación de la refinería.
Descriptores: Consumo energético, refinerías de petróleo, eficiencia energética, contaminación del aire, gasolinas.

Introduction

Oil refineries are big energy-consuming industrial facilities (Rossi *et al.*, 2020; Ulyev *et al.*, 2018). Several authors, such as (Ocic, 2005), state that the equivalent energy consumption relative to the processed crude, ranges between 4 % and 8 % (Szklo & Schaeffer, 2007; Ochoa & Jobson, 2015) between 7 % and 15 %, and (Worrel *et al.*, 2015), between 27 % and 35 % with data calculated by this agency. Therefore, energy consumption in an oil refinery may vary in time, due to the type of processed crude, the complexity of the refinery (U.S. Energy Information Administration, 2012), loading capacity, and other operational factors (Hui *et al.*, 2016).

Additionally, the processes with a greater energy intensity in relation to a major load capacity are atmospheric distillation "AD", vacuum distillation "VD", catalytic reforming "CR", catalytic cracking "CC", hydrocracking "HC", hydrotreatment "HT", coking "CK", and alkylation "AK" (Worrel *et al.*, 2015). The energy consumption of AD and VD is 35 % and 45 % of the total of the different processes (Szklo & Schaeffer, 2007), and more than 80 % of the energy consumption results from the refinery products, including refinery gas (RG), petroleum coke (PC), liquid gas (LG), fuel oil (FO), and other refined products (Wang *et al.*, 2004), which are used for direct heating or for vapor generation; additionally electricity (EL) is used to power pumps, compressors and other ancillary equipment (Worrel *et al.*, 2015).

In recent years, the processed crude has become heavier and the established refineries have focused in procuring lighter fuels such as gasoline (Demirbas & Bamufleh, 2017). Among the different oil-derived products produced from an oil barrel in a United States refinery, 45 % to 48 % is gasoline (U.S. Energy Information Administration, 2019) and, according to (Wang *et al.*, 2004), 53.7 % of the energy used in a particular refinery is used in the production of fuel.

In contrast, although refineries satisfy society's energy demands, they can also affect air quality (Ragothaman & Anderson, 2017). The World Health Organization (WHO) has identified polluted air as the biggest health hazard and, thus, efforts are needed to maintain a good air quality (World Health Organization, 2020). This industry is responsible for the emission of several air pollutants (Kalabokas *et al.*, 2001; Hadidi *et al.*, 2016), emitting millions of tons (MM tons) to the air with a potential health risk (Wakefield, 2007). Some of the pollutants emitted by this industry include carbon monoxide (CO), particles (PM), nitrogen oxides (NO_x), sulfur oxides (SO_x), and volatile organic compounds (VOC) (Worrel *et al.*, 2015).

To this date, Mexico has six oil refineries (Cadereyta, Madero, Minatitlán, Salamanca, Salina Cruz and Tula), which process three types of crude oils (Olmeca, Istmo and Maya), which are considered as super light, light, and heavy, respectively (Petróleos Mexicanos, 2018). According to the Energy Information System the six refineries had a gasoline production yield of 30.2 % in 2007 and 28.1 % in 2017 (Sistema de Información Energética, 2019).

According to data obtained from the National Institute of Transparency, Access to Information and Personal Data Protection (INAI), the Transformation Subsector of Petróleos Mexicanos (INAI, 2017), reported that the energy self-consumption of the Oil Refining Sector (SNR) was only fuel oil (FO) and electricity (EL), which represented 8 % of the equivalent energy relative to the total processed crude in 2007 and 9 % in 2016. Additionally. Mexico's oil refineries emitted a total of 326,456 tonnes (tons) in 2016, with a proportion of 84 % (SO_x), 6 % (NO_x), 4 % (PM) and 5 % (VOC).

Finally Miranda (2018), published an informative note in the newspaper La Jornada, where it is mentioned that gasoline importation increased 63 % and production decreased 50 %, that is, Refining National System decreased from a production of 437,000 barrels per day (B/D) in 2013, to 217,000 B/D in the first half of 2018. On the other hand, the current situation limits fuel offer for the next years, implying that Mexico will continue importing gasoline.

In this sense, the set-up of the oil refining industry in Mexico has the main objective of satisfying the demand of different fuels, particularly of gasolines, consuming the greater volume of the crudes in the country and reporting clearly and timely the energy and environmental impact that this industry will have. However, this depends on a series of challenges which are the bases of study of the present paper, and which will be decisive in the fuel transformation processes.

The principal objective of this study is to estimate the energy consumption and the emissions of CO, SO_x, NO_x, PM and VOC of the Mexican oil refining industry for the year 2030, with the idea of contributing and extending new information on the atmospheric emissions of this industry, applying different refining technologies used to satisfy the gasoline demand.

Consequently, this paper, after the Introduction, begins with information on the possible gasoline demand scenarios in Mexico, after which the energy consumption and atmospheric emissions estimates are modeled. Finally, the last two sections emphasize and discuss its results and conclusions, respectively.

Gasoline demand scenarios in Mexico

In a paper published in (Bauer *et al*., 2003) examined the impact of the gasoline demand in Mexico, as a consequence of the increase in the number of vehicles which circulate when a certain per capita level is reached. Thus, the four scenarios in gasoline demand calculated by these authors are labeled as A, B, C and D in this paper. The first scenario (A) was based on the historical yearly car increase (4.3 %) for the period 1980-2000, and of 4 % for the period 2000-2030. Scenarios B, C and D were established considering a yearly increase in the average gross national product (GNP) of 3.7, 5.3 and 6.2 %, respectively (2000-2030), based on the Gompertz Curve to obtain the number of vehicles as a function of the per capita income and, in consequence, as a function of the year when such income is reached. In this way, the gasoline demand scenarios for the year 2030 established by the authors are: 1306000, 2142000, 2765000 and 2904000 B/D, respectively.

On the other hand, the Mexican Department of Energy (Secretaría de Energía, 2016) reported that the gasoline demand will have an average yearly increase of 1.9 % for the period 2016-2030, that is 834000 B/D to 1063000 B/D in 2030. Finally, a particular scenario was developed by performing a correlation Montecarlo simulation between the historical gasoline demand relative to the relevant macroeconomic indicators for this study (using the Crystal Ball program). These indicators are the currency exchange, the national consumer price index (NCPI), the GNP, the balance of trade and, additionally, the country's population. A correlation analysis was performed for each of these and forming groups of indicators with the historical demand of gasoline. From this analysis one can conclude that it is convenient to relate the gasoline demand with the GNP, the NCPI and the population, since a better correlation (R^2= 0.8395) was obtained with a fuel demand scenario of 1193000 B/D for the year 2030.

Table 1. Gasoline demand scenarios (B/D)

δ					
A	B	C	D	s	m*
1,306,000	2,142,000	2,765,000	2,904,000	1,063,500	1,193,900

Source: (Bauer *et al*., 2003)

(Secretaría de Energía, 2016)

Own elaboration

Modeling of the energy consumption and atmospheric emissions

Different projections were determined by modeling four types of refineries (R1 "hydroskimming", R2 "cracking", R3 "hydrocracking" and R4 "full conversion"), three types of crudes (Olmeca, Istmo and Maya), and eight types of processes (AD "atmospheric distillation", VD "vacuum distillation", CR "catalytic reformation", CC "catalytic cracking", HC "hydrocracking", HT "hydrotreatment", CK "coking", AK "alkilation").

The steps for the modeling and estimation for the six energy sources (EL "electricity", NG "natural gas". RG "refinery gas", PC "petroleum coke", FO "fuel oil", LG "liquid gas") and five types of atmospheric pollutants (SO_x "sulfur oxides", NO_x "nitrogen oxides", CO "carbon monoxide", PM "particles", VOC "volatile organic compounds") are then described:

Step 1. Required crude volume

This was calculated from the following equation:

$$\mu = \left[\frac{\delta - P}{\left(\frac{\lambda_{i,r}}{100} * \frac{\gamma}{100} \right)} \right] \tag{1}$$

Where:

μ = crude oil volume (B/D)
δ = gasoline demand (B/D)
P = current gasoline production (325000 B/D)
$\lambda_{i,r}$ = gasoline production yield (% vol.)
i = type of analyzed crude (Olmeca, Istmo, Maya)
r = type of refinery (R1, R2, R3, R4)
γ = production efficiency (100 %)

Table 2. Gasoline yield by type of crude oil and refinery analyzed (% Vol.)

	λ			
i	r			
	R1	R2	R3	R4
Olmeca	21.41	33.06	47.16	54.55
Istmo	18.51	29.97	39.78	55.23
Maya	15.30	23.00	33.43	54.57

Source: (Baird, 1996)

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The data base required that feeds Equation 1 is given in Table 1 and 2.

Step 2. Carrying capacity for each type of analyzed process

This was calculated from the following equation:

$$þ = (\mu)*\left(\frac{T_j}{100}\right) \quad (2)$$

Where:

þ = carrying capacity (B/D)
μ = crude oil volume (B/D)
T_j = operation rate (% Vol.)
j = process type (AD, VD, CR, CC, HC, HT, CK, AK)

The operation rates for the different types of analyzed processes are given in Table 3.

Step 3. Energy consumption by type of process

Energy consumption was calculated using the following equation using the data base shown in Table 4:

$$£ = (þ) * (\varepsilon_e) / 1*10\text{^}6 \quad (3)$$

Where:

£ = energy consumption in million British thermal units per day (MMBtu/D)
þ = carrying capacity (B/D)
ε_e = specific energy (British thermal unit per barrel "Btu/B")
e = minimum (x), maximum (y), average (z)

Step 4. Energy source consumed by type of process

The following equation is used:

$$Ƒ = (£) * (f_j / 100) \quad (4)$$

Where:

Ƒ = energy consumption by energy source (MMBtu/D)
£ = energy consumption (MMBtu/D)
f = energy source (%) (EL, NG, RG, PC, FO, GL)
j = process type (AD, VD, CR, CC, HC, HT, CK, AK)

Table 3. Operating rate by type of crude and refinery analyzed (% Vol.)

j	Olmeca				Istmo				Maya			
	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4
AD	μ											
	T											
VD	----	38	29	38	----	43	43	43	----	61	22	61
CR	19	17	31	23	16	15	27	28	14	15	19	32
CC	----	32	----	31	----	28	----	28	----	24	----	23
HC	----	----	16	6	----	----	13	8	----	----	8	11
HT	25	23	34	29	21	19	29	33	17	18	23	35
CK	----	----	----	4	----	----	----	15	----	----	----	32
AK	----	5	----	6	----	4	----	7	----	3	----	5

Source: (Baird, 1996)

Table 4. Specific energy by type of process

j	*e*		
	x	*y*	*z*
AD	85,389	189,753	137,571
VD	47,438	113,852	80,645
CR	208,729	341,556	275,142
CC	47,438	170,778	109,108
HC	161,290	322,581	241,935
HT	56,926	170,778	113,852
CK	113,852	237,192	175,522
AK	332,068	341,556	336,812

Source: Own elaboration based on (Pellegrino *et al.*, 2007)

Table 5 gives the energy percentage by type of analyzed source in percentage.

Step 5. Emissions estimations

The following equation is used as indicated by the United States Environmental Protection Agency (U.S. Environmental Protection Agency, 2020)

$$E = (F) * (C_f) \quad (5)$$

Where:

E = emission of each type of pollutant (tons per day "tons/D")
F = energy consumption by energy source (MMBtu/D)
c_f = emission factor of each type of pollutant (tons/MMBtu)
c = pollutant (SO_x, NO_x, CO, PM, VOC)
f = energy source (EL, NG, RG, PC, FO, GL)

Table 6 gives the emission factor of each type of pollutant in tons/MMBtu

Finally, equation 6 summarizes the matrix that was used to estimate the total emission estimates by type of analyzed crude and refinery.

$$\Lambda_{i,r} = \Sigma[(F) * (C_f)]_j \quad (6)$$

Where:

Λ = total emissions of pollutants (tons/D)
i = type of analyzed crude (Olmeca, Istmo, Maya)
r = type of refinery (R1, R2, R3, R4)
F = energy consumption by energy source (MMBtu/D)
c_f = emission factor of each type of pollutant (tons/MMBtu)
j = process type (AD, VD, CR, CC, HC, HT, CK, AK)

Figure 1 shows the block diagram for determining energy consumption and atmospheric emissions, considering the type of refining technology.

Results and discussion

Figure 2 shows the volume of processed crude for the projections PA, PB, PC, PD, Ps and Pm, required to satisfy the gasoline demand for the year 2030.

Table 5. Energy consumed by type of energy source and process analyzed (%)

j	*f*					
	EL	NG	RG	PC	FO	LG
AD	6.2	25.7	46.2	17	3.1	1.8
VD	3.9	26.3	47.2	17.4	3.2	2.00
CR	8.7	21	48.3	15.5	4.6	1.8
CC	12.5	5.5	10	70.9	0.7	0.4
HC	49.9	13.7	24.6	9.1	1.7	1
HT	47.9	14.2	25.6	9.5	1.8	1
CK	23	21.1	37.9	14	2.5	1.4
AK	37.6	17.1	30.7	11.3	2.1	1.3

Source: Own elaboration based on (Pellegrino *et al.*, 2007)

Table 6. Emission factors by type of energy source

f	c_f				
	SO_x	NO_x	CO	PT	COV
EL	6.6E-04	2.5E-04	3.2E-05	1.8E-04	1.8E-06
NG		6.4E-05	3.7E-05	1.4E-06	2.7E-06
RG		6.4E-05	3.7E-05	1.4E-06	2.7E-06
PC	1.1E-03	4.3E-04	1.1E-05	3.3E-04	2.3E-06
FO	7.7E-04	1.2E-04	1.6E-05	2.0E-05	2.5E-06
LG		9.4E-05	3.7E-05	3.2E-06	2.7E-06

Source: Own elaboration based on (Pellegrino *et al.*, 2007)

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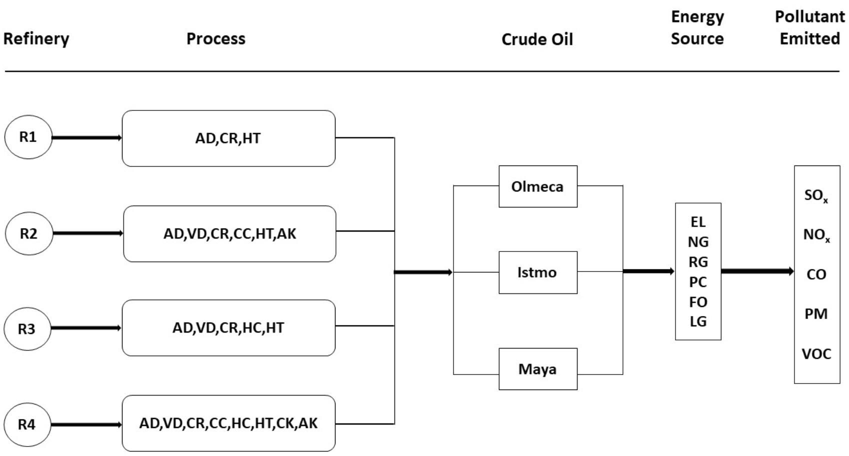

Figure 1. Simple block diagram used to estimate atmospheric emissions

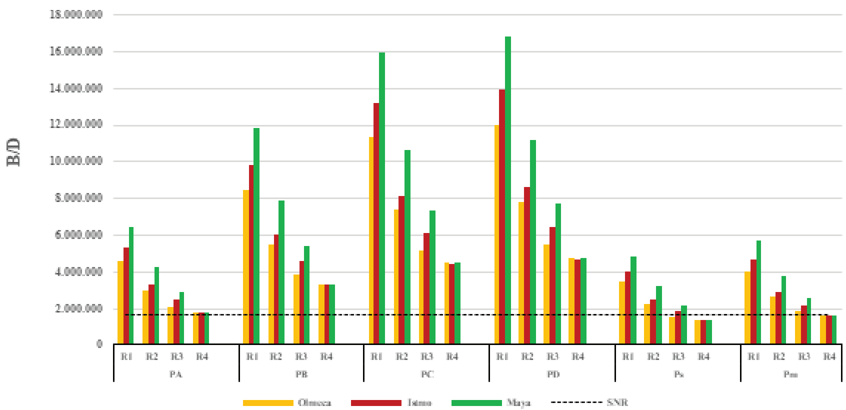

Figure 2. Volume of processed crude

The figure clearly shows how the required crude volumes for three of the six projections exceeds, by much, the planned volumes that will be sent to the national refinery system NRS (SENER, 2016) (dotted line). Only the scenario based on the vehicular growth tendency (PA), the one suggested by the Mexican Department of Energy (Ps), and the one modeled by the Montecarlo program (Pm), almost completely agree for a very complex refinery (R4) and for the three types of crude.

Table 7 shows the carrying capacity for the different processes which are a function of the carrying capacity that feeds the DA process for each refinery and type of crude analyzed.

Based on Table 7, the carrying capacity minima and maxima for the different analyzed processes are obtained when using one type of refinery and crude as follows: VD (R3-olmeca, R2-maya), CR (R4-olmeca, R1-maya), CC (R4-maya, R2-maya), HC (R4-olmeca, R3-olmeca), HT (R4-olmeca, R1-olmeca), CK (R4-olmeca, R4-maya) and AK (R4-maya, R2-olmeca).

With the idea of reducing the presentation of the results obtained in this study, only the highest projections (PD) are presented below.

Figure 3 show at first glance, it can be seen that the process that uses the most energy is atmospheric distillation (AD) regardless of the type of analyzed projection. It can also be seen that, regardless of the minima, maxima or average values, the use of Maya crude implies a higher energy consumption in very complex refineries (R4) relative to the complex ones (R3).

In this same sense Figure 4 show type of energy consumed considering an average consumption

From Figure 4, it can be appreciated that both liquid gas (LG) and fuel oil (FO) are sources with the least energy requirement to satisfy the gasoline demand. Most of the energy consumption occurs both for atmospheric distillation (AD) and catalytic reforming (CR). For CR, the difference in energy consumption between the different types of refineries is not great, in contrast with AD, where energy consumption practically triplicates when a simple refinery is used (R1) when compared to a very complex one (R4). The percentage increase between these two types of refineries is progressive as the crude becomes heavier. On the other hand, and in the context of atmospheric distillation, the use of LG and fuel oil in a complex refinery (R3) consumes bet-

Table 7. Carrying capacity (B/D)

Proceso	OLMECA				ISTMO				MAYA			
	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4
PA												
VD	----	1,134,708	612,397	687,689	----	1,415,036	1,066,079	767,855	----	2,586,001	652,953	1,089,940
CR	877,677	508,601	636,527	416,660	868,007	480,091	664,579	497,782	877,706	622,295	568,381	569,131
CC	----	952,810	----	555,277	----	926,009	----	492,045	----	1,032,183	----	417,136
HC	----	----	340,334	112,882	----	----	324,731	148,917	----	----	224,547	192,119
HT	1,134,267	674,771	708,105	517,367	1,123,990	638,190	724,554	583,573	1,081,601	757,929	661,698	626,298
CK	----	----	----	74,038	----	----	----	265,366	----	----	----	575,747
AK	----	157,061	----	114,051	----	138,590	----	123,251	----	113,071	----	95,673
PB												
VD	----	2,101,696	1,134,277	1,273,732	----	2,620,918	1,974,583	1,422,215	----	4,789,770	1,209,395	2,018,778
CR	1,625,625	942,026	1,178,969	771,734	1,607,716	889,221	1,230,928	921,989	1,625,681	1,152,610	1,052,751	1,054,140
CC	----	1,764,787	----	1,028,479	----	1,715,146	----	911,362	----	1,911,800	----	772,616
HC	----	----	630,363	209,080	----	----	601,464	275,823	----	----	415,904	355,842
HT	2,100,880	1,249,806	1,311,546	958,263	2,081,844	1,182,050	1,342,013	1,080,890	2,003,332	1,403,830	1,225,592	1,160,023
CK	----	----	----	137,133	----	----	----	491,508	----	----	----	1,066,393
AK	----	290,907	----	211,245	----	256,696	----	228,285	----	209,429	----	177,205
PC												
VD	----	2,822,311	1,523,189	1,710,460	----	3,519,560	2,651,614	1,909,853	----	6,432,052	1,624,063	2,710,962
CR	2,183,008	1,265,021	1,583,206	1,036,340	2,158,958	1,194,110	1,652,980	1,238,113	2,183,082	1,547,809	1,413,711	1,415,576
CC	----	2,369,885	----	1,381,116	----	2,303,223	----	1,223,844	----	2,567,304	----	1,037,525
HC	----	----	846,498	280,768	----	----	807,690	370,396	----	----	558,507	477,850
HT	2,821,214	1,678,330	1,761,239	1,286,826	2,795,652	1,587,343	1,802,153	1,451,497	2,690,220	1,885,165	1,645,814	1,557,764
CK	----	----	----	184,152	----	----	----	660,033	----	----	----	1,432,030
AK	----	390,651	----	283,675	----	344,710	----	306,557	----	281,237	----	237,964
PD												
VD	----	2,983,090	1,609,961	1,807,900	----	3,720,059	2,802,669	2,018,652	----	6,798,468	1,716,582	2,865,398
CR	2,307,368	1,337,086	1,673,397	1,095,378	2,281,948	1,262,135	1,747,146	1,308,645	2,307,446	1,635,983	1,494,246	1,496,217
CC	----	2,504,891	----	1,459,794	----	2,434,431	----	1,293,563	----	2,713,557	----	1,096,630
HC	----	----	894,721	296,762	----	----	853,702	391,496	----	----	590,323	505,072
HT	2,981,931	1,773,940	1,861,572	1,360,133	2,954,913	1,677,770	1,904,816	1,534,185	2,843,474	1,992,558	1,739,571	1,646,505
CK	----	----	----	194,642	----	----	----	697,633	----	----	----	1,513,609
AK	----	412,905	----	299,835	----	364,347	----	324,021	----	297,258	----	251,520
Ps												
VD	----	854,790	461,327	518,045	----	1,065,965	803,091	578,435	----	1,948,068	491,878	821,066
CR	661,165	383,136	479,504	313,875	653,881	361,659	500,636	374,986	661,188	468,783	428,169	428,734
CC	----	717,764	----	418,297	----	697,575	----	370,664	----	777,557	----	314,234
HC	----	----	256,378	85,036	----	----	244,624	112,181	----	----	169,154	144,726
HT	854,458	508,314	533,424	389,740	846,716	480,757	545,816	439,613	814,784	570,958	498,466	471,798
CK	----	----	----	55,774	----	----	----	199,903	----	----	----	433,717
AK	----	118,316	----	85,916	----	104,402	----	92,847	----	85,178	----	72,072
Pm												
VD	----	1,005,087	542,441	609,133	----	1,253,393	944,298	680,141	----	2,290,596	578,365	965,434
CR	777,417	450,502	563,815	369,064	768,853	425,249	588,663	440,920	777,444	551,209	503,454	504,118
CC	----	843,969	----	491,846	----	820,229	----	435,838	----	914,274	----	369,486
HC	----	----	301,457	99,988	----	----	287,636	131,906	----	----	198,897	170,173
HT	1,004,697	597,691	627,216	458,267	995,594	565,288	641,787	516,910	958,047	671,349	586,111	554,754
CK	----	----	----	65,581	----	----	----	235,052	----	----	----	509,978
AK	----	139,119	----	101,023	----	122,759	----	109,172	----	100,155	----	84,744

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ween 7-18 %, 28-43 %, and 57-64 % more energy than in a very complex refinery (R4), if Olmeca, Istmo and Maya crudes are refined.

Figure 5 show the emissions by type of analyzed pollutant for three energy sources (EL, FO and RG) at the different types of refineries, types of crudes and processes studied, considering an energy consumption average.

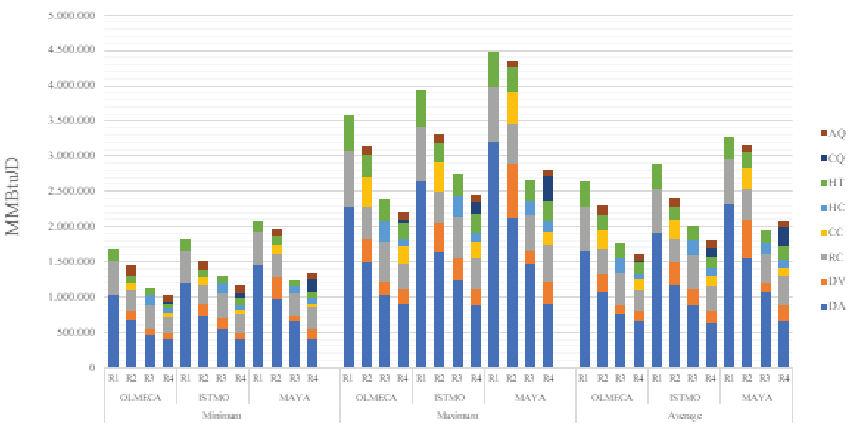

Figure 3. Maximum, minimum and average energy consumption

Figure 4. Type of energy consumed

Figure 5 shows that fuel oil (FO) generates the least emissions when used as a heat source in the refineries. In contrast, refinery gas (RG) is comparable only in total particles (PM). The use of electricity as an energy source for refineries implies and emission of up to 3, 6, 7, 33, and 2.5 times more SOx, NOx, CO, PM and VOC, respectively. On the other hand, the use of refinery gas (RG) implies the emission of 7, 33 and 15 times more NOx, CO and VOC, respectively. The proportion of emitted pollutants varies according to the three used sources of energy.

Figure 6 gives the total emissions of the analyzed pollutants considering an average energy consumption for each type of refinery and crude oil for the different projections in the study.

In Figure 6 it can be seen that regardless of the analyzed projection, refinery R3 processing Olmeca crude has the lower emissions and that R2 processing Maya crude has the highest, with a difference, in ton/day, of 350 for PA, 648 (PB), 870 (PC), 952 (PD), 273 (Ps) and 310 (Pm).

Table 8 shows the energy consumption relative to the total consumption by refinery type and crude processed, for a minimum consumption, an average and a maximum consumption.

Results from Table 8 show that the Interval of minimum, maximum and average energy consumption in proportion to the energy used for processes AD + VD is between 40.4 % and 65.2 %, 42.5 % and 66 %, and 43.6 % and 66.5 %, respectively, with the lowest value when R4 is used with Maya crude, and the highest with an R2 refinery using this same crude.

Figure 7 gives the equivalent energy consumption relative to the total processed crude, regardless of the analyzed projection, using data from this study (calculated) and reference data cited in this document (Ocic, 2005; Worrel, 2015).

This figure shows that the calculated data for the equivalent energy consumption relative to the total processed crude is within the lower interval of the reference data cited by Szklo, 2005 (4 %), and within the highest reference as calculated with the data EPA, 2015 (35 %).

Figure 5. Atmospheric emission estimates

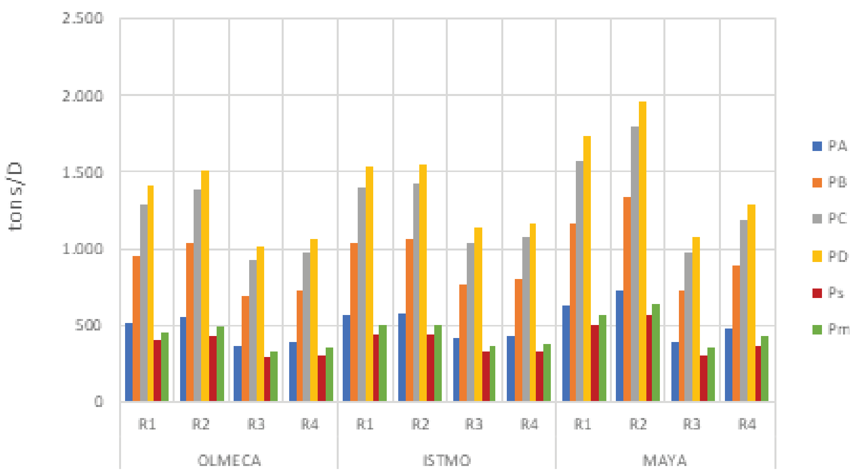

Figure 6. Total emissions estimates

Table 8. Energy consumption relative to the total consumption (percentage)

Proceso	OLMECA				ISTMO				MAYA			
	R1	R2	R3	R4	R1	R2	R3	R4	R1	R2	R3	R4
Minimum												
DA	61.3%	46.2%	40.9%	39.0%	64.9%	48.8%	42.7%	34.2%	69.1%	48.8%	52.9%	30.2%
DV	----	9.8%	6.7%	8.3%	----	11.7%	10.2%	8.2%	----	16.4%	6.5%	10.2%
RC	28.7%	19.3%	30.5%	22.1%	26.0%	17.5%	28.1%	23.4%	23.1%	17.4%	25.0%	23.4%
CC	----	8.2%	----	6.7%	----	7.7%	----	5.3%	----	6.6%	----	3.9%
HC	----	----	12.6%	4.6%	----	----	10.6%	5.5%	----	----	7.6%	6.1%
HT	10.1%	7.0%	9.3%	7.5%	9.2%	6.3%	8.4%	7.5%	7.8%	5.8%	7.9%	7.0%
CQ	----	----	----	2.2%	----	----	----	6.8%	----	----	----	13.0%
AQ	----	9.5%	----	9.6%	----	8.0%	----	9.2%	----	5.0%	----	6.2%
Average												
DA	62.9%	46.7%	42.4%	40.2%	66.5%	49.1%	44.1%	35.5%	70.7%	48.7%	54.3%	31.3%
DV	----	10.5%	7.3%	9.0%	----	12.4%	11.2%	9.0%	----	17.3%	7.1%	11.1%
RC	24.1%	16.0%	26.0%	18.6%	21.8%	14.4%	23.8%	19.9%	19.4%	14.2%	21.0%	19.8%
CC	----	11.9%	----	9.8%	----	11.0%	----	7.8%	----	9.4%	----	5.8%
HC	----	----	12.2%	4.4%	----	----	10.2%	5.3%	----	----	7.3%	5.9%
HT	13.0%	8.9%	12.0%	9.6%	11.8%	8.0%	10.8%	9.7%	9.9%	7.2%	10.2%	9.1%
CQ	----	----	----	2.1%	----	----	----	6.8%	----	----	----	12.8%
AQ	----	6.1%	----	6.2%	----	5.1%	----	6.0%	----	3.2%	----	4.1%
Maximum												
DA	63.8%	47.0%	43.2%	40.7%	67.3%	49.2%	44.7%	36.1%	71.5%	48.7%	55.1%	31.9%
DV	----	10.9%	7.7%	9.4%	----	12.9%	11.7%	9.4%	----	17.8%	7.4%	11.7%
RC	22.0%	14.5%	23.8%	17.0%	19.8%	13.0%	21.7%	18.2%	17.6%	12.8%	19.2%	18.2%
CC	----	13.6%	----	11.3%	----	12.5%	----	9.0%	----	10.6%	----	6.7%
HC	----	----	12.0%	4.3%	----	----	10.0%	5.2%	----	----	7.2%	5.8%
HT	14.2%	9.6%	13.2%	10.5%	12.8%	8.6%	11.8%	10.7%	10.9%	7.8%	11.2%	10.0%
CQ	----	----	----	2.1%	----	----	----	6.8%	----	----	----	12.8%
AQ	----	4.5%	----	4.6%	----	3.8%	----	4.5%	----	2.3%	----	3.1%

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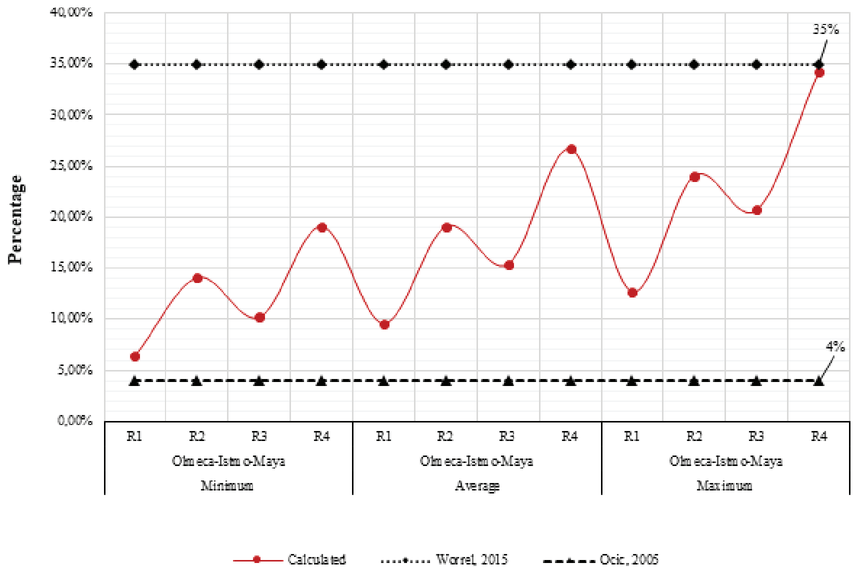

Figure 7. Equivalent energy consumption relative to the total processed crude oil

Therefore, in analysis of the minimum energy consumption, the calculated interval lies between 6.4 % and 19.1 %, an average consumption between 9.6 % and 26.7 %, and a maximum consumption 12.7 % and 34.3 %. Additionally, an R4 refinery shows the highest equivalent energy consumption and an R1 refinery shows the lowest.

Conclusions

It may be thought that the quantity of required crude needed to satisfy the gasoline demand for the year 2030 is low (two million barrels per day), since it is equal to the quantity produced to date since the last couple of years. However, one has to consider that very complex refineries will be used which will be very efficient. On the other hand, when refining a lower quantity of crude, emissions, obviously, will be lower.

Refining very heavy oils in very complex refineries (R4) has a small disadvantage when considering energy consumption. Since the tendency in the very near future is precisely to extract this type of crudes in Mexico since these are the most abundant, then there will be no more solution than to bet for these types of refineries. This disadvantage may be compensated by their greater conversion efficiency and by using les quantity of crude to satisfy the demand and, consequently, will emit a lower quantity of atmospheric pollutants. Based on the scenario proposed by Bauer *et al.* (2003), that a strong economy increases the acquisition power of the population in order to obtain material goods (including automobiles), it also implies a greater quantity of atmospheric emissions. Therefore, an equilibrium should be reached between these two processes.

Among the consumed energy sources in the refineries to heat different processes, liquid gas may be the best option in terms of energy savings. On the other hand, its emission factors are low relative the other types of energy sources, except for natural gas (NG) which has lower factors for NO_x and PM. The problem would then be evaluating which would be more convenient to obtain a greater socio-economic benefit: reduce emissions to the atmosphere or to lower operation costs of the refinery. The availability of an adequate energy source is also implicit, since sometimes the best option is not available or, it may be available at a higher cost. It all winds up in a cost-benefit study.

It is important to know the type of pollutant whose emission needs to be reduced if such were the case. If the problem is SOx, refinery gas (RG) would be the best option. If it were total particles (PM), one could either use fuel oil (FO) or refinery gas (RG).

Therefore, it is important to reach beyond the idea that "the best energy source is that one that pollutes the least". Rather, one needs to analyze the advantages and disadvantages of using each one of them and their relation to the quantity of emissions to the atmosphere.

The use of electricity (EL) for the operation of pumps, compressors and ancillary equipment showed high emissions; this can be the consequence of its generation and distribution to the refinery, where some type of thermoelectric or carbo-electric source and not a different source of generation. The latter is because there is no information from PEMEX. However, if the pollutant quantity to used energy variables are analyzed, electrical energy shows a low relationship.

In relation to the different analyzed processes, the atmospheric distillation and vacuum distillation units should be emphasized since they are characterized by a high energy consumption. This means that their operation has serious implications relative to the product revenues and operation costs.

The complexity of a refinery in terms of a higher gasoline production yield is an important factor for energy consumption and atmospheric emissions.

Mexico's possible refineries need to adapt themselves to different operation scenarios, such as changes in the crude's yield, the quality of the product, variations in the prices of the crude and of the refined products.

It is important to develop and apply perspectives than maximize productivity and minimize energy consumption in constant change scenarios.

In relation with the energy reform in Mexico and the posture of the recently elected President (Andrés Manuel López Obrador), of building a new refinery, this document may help guide to the authorities of the energy sector to plan for a better yield in the production of gasoline and satisfy the possible demand for the future years, as well as minimize atmospheric emissions.

Finally, the demand for gasoline could vary in the future mainly due to the introduction of hybrid or electric vehicles, therefore it would be important to carry out research work that will consider this variable in the projection of the fuel.

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