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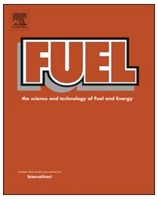

Full Length Article

Estimation of U.S. refinery water consumption and allocation to refinery products

Pingping Sun[a], Amgad Elgowainy[a,*], Michael Wang[a], Jeongwoo Han[a], Robert J. Henderson[b]

[a] *Argonne National Laboratory, Energy Systems Division, 9700 South Cass Avenue, Building 362, Lemont, IL 60439, United States*
[b] *Jacobs Consultancy, 525 West Monroe, Chicago, IL 60661, United States*

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ABSTRACT

Increasing stress on the global water supply necessitates the measurement of water consumption as a sustainability metric to evaluate energy production, including the production of transportation fuels (gasoline, diesel, jet fuel) at petroleum refineries. This study estimated refinery water consumption for petroleum fuels by considering three typical refinery configurations (cracking, light coking, and heavy coking) that process different crude qualities (e.g., American Petroleum Institute Gravity (API) gravity and sulfur content). The results showed that refinery water consumption was 0.34, 0.44, and 0.47 bbl water/bbl crude (L water/L crude) for cracking, light coking, and heavy coking configurations, respectively. The water consumption for a specific refinery product was estimated using an energy allocation approach at the process unit level. The results indicated that gasoline production consumes the largest amount of water, 0.60–0.71 gal water/gal gasoline (0.60–0.71 L water/L gasoline), due to the energy-intensive (and thus water-intensive) processing of gasoline components (mainly sourced from alkylation, reformer, and fluid catalytic cracking units). In contrast, jet fuel production consumes the least water, 0.09 gal water/gal jet fuel, for all three refinery configurations, because it is sourced directly from the crude distillation unit with minimal post-treating. The consumption of diesel is most sensitive to refinery configuration with 0.20, 0.30, and 0.40 gal water/gal diesel (L water/L diesel) for cracking, light coking and heavy coking configurations, respectively. This is mainly because as configuration complexity increases to process heavier and sourer crudes, a sizable burden of hydrogen production from steam methane reforming unit is allocated to diesel fuel production (including diesel sulfur removal). The trend of water consumption associated with these refinery products is consistent with the energy consumption for their production.

1. Introduction

Two essential elements of modern society, energy and water, are inextricably connected. The production of energy requires significant amount of water, and in turn, the extraction, treatment, distribution, and use of water along with waste water treatment consume a large amount of energy [1,2]. For example, Water for Energy [1] reported that in 2010 about 15% of the world's total water withdrawals, or 583 billion cubic meters (bcm), was used for energy production. Of that, about 11.3%, or 66 bcm of water, was consumed (the net of volume withdrawn and that returned to its source). Globally, energy-related water consumption is projected to increase significantly, by 100% from 2010 to 2035. This will further deteriorate the balance between fresh water supply and demand, which will be stressed by economic growth, population growth, urbanization, and improved standards of living, along with other factors [3]. The scarcity of water is deemed a top global risk in terms of both impact and likelihood over the next decade [3]. For the United States, the government report expected a continuation of freshwater shortages into the future. Regionally, water shortages are expected within individual states under average conditions over the next 10 years [4]. Furthermore, the regional imbalance between water supply and demand, the development of unconventional

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Abbreviations: Bcm, billion cubic meter; CEC, California Energy Commission; API gravity, American Petroleum Institution gravity; LtCoking, light coking configuration; WWTP, waste water treatment plants; SGP, saturates gas plant; UnSGP, unsaturated gas plant; CW, cooling water; NHT, naphtha hydrotreating; BenSat, benzene saturation; GOHT, gas oil hydrotreating; Amine Regen, Amine Regeneration; Demin plant, demineralization plant; MLB, thousands of pounds; LPG, liquefied petroleum gas; GHG, greenhouse gas; MMscf, million standard cubic feet; LP, Linear Programming; PADD, Petroleum Administration for Defense District; Crk, cracking configuration; HvyCoking, heavy coking configuration; CDU, Crude distillation unit; FCC, fluidized catalytic cracking; BPSD, barrel per calendar day; VDU, Vacuum distillation unit; Isom, Isomerization; DHT, diesel hydrotreating; SMR, steam methane reforming; SW stripper, sour water stripper; SCFD, standard cubic feet per day; BFW, boiler feed water; LHV, low heating value; GREET, The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model

[*] Corresponding author.

E-mail address: aelgowainy@anl.gov (A. Elgowainy).

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gas and oil, and the dedicated growth of biofuel crops, will further complicate the future water supply issue [3].

The interdependence of the production/consumption of energy and water, and thus their inextricable impacts on the environment, society, economics, and human health, make it vital to produce and consume water and energy in a sustainable, socially responsible and environmentally friendly way. Increasingly, water serves as an important criterion through which to assess energy projects for economic and environmental viability; therefore, it is necessary to thoroughly track the water consumption footprints associated with energy production.

The transportation sector is one of the largest energy consumers in the United States, contributing 26% of the nation's total greenhouse gas (GHG) emissions in 2014 [5]. U.S. refineries constitute 23% of the world's total refining capacity [6] and consume large quantities of energy. As much as 10% of the energy content of crude oil is consumed in the processing steps within refineries, and a significant amount of this energy is subsequently rejected via cooling in the form of thermal energy losses. Therefore, significant quantities of water—primarily for processing and cooling—are consumed to produce petroleum fuels in refineries.

Thus, the current study focuses on studying refinery water consumption, evaluating the water consumption of different petroleum products as a function of different refinery configurations. Variations within refinery configurations are in turn correlated to crude oil American Petroleum Institute (API) gravity and sulfur content. Jacobs Consultancy constructed and implemented a refinery Linear Programming (LP) model, the details of which are described in Han et al., to assist in the evaluation [7].

Previous studies investigated water usage in U.S. refineries [8–11]. Their research estimated that processing 1 gallon (3.79 L) of crude oil in U.S. refineries requires 1.0–1.9 gallons (3.79–7.19 L) of water, with a median of 1.5 gallons (5.68 L) of water. Earlier research [12] showed similar refinery water consumption, 0.9 bbl water/bbl crude (0.9 L water/0.9 L crude), but with a much wider range of 0–7.2 bbl water/bbl crude (0–7.2 L water/L crude). One recent publication regarding refinery water consumption data is the California Energy Commission (CEC) report [13] listing California water consumption. The report showed that in 2012, California refineries used approximately 1.1 L of net consumptive water per liter of crude (including fresh water, recycled water, degraded water, and waste water). However, the freshwater consumption was about 0.53 L water/L crude, with a maximum of 1.38 L water/L crude and a minimum of zero. Although the data might not be representative in a national range, the difference between water consumption from all sources and freshwater consumption sheds light on freshwater conservation.

In terms of water consumption per refinery product, Wu and Chiu 2011 [14] research showed that producing 1 gal (3.79 L) of product can consume as little as 0.5 gal (1.89 L) of water to as much as 2.5 gal (9.46 L) water, depending on the refining processes while accounting for the slight volume expansion when crude is converted into refinery products [14]. The CEC report showed that the water use intensity of refineries ranged from 0.74 to 1.41 L water/L refined product.

These studies were conducted at various times with various surveying pools and research approaches, reflecting the water consumption patterns of the facilities at that time. In recent years, the evolving crude slate change (increasing shares of Canadian oil sand and domestic shale oil), adaptive refinery remodeling/expansion, process technology advancement, efficiency improvement, and resource conversation practices along with (or motivated by) more stringent regulations, will likely result in changes in water consumption patterns, thus providing an incentive for a new study of U.S. refinery water consumption to reflect current practice.

This study focuses on the following:

1. Estimate the typical water consumption for an oil refinery and examine its dependence on refinery design/configuration.
2. Compare the results of the current study with those of previous studies to examine the potential change of refinery water consumption patterns.
3. Develop an approach to allocate refinery water consumption to each refinery product.
4. Examine whether the water consumption intensity of each refinery product correlates with its energy consumption intensity.

Refinery water consumption allocation to different products is of great interest because it can reveal the water consumption intensity for individual refinery products, due to different production pathways consisting of various processes that differ significantly in water consumption. Such variation of refinery products in energy consumption and in GHG emission has been observed previously [15], and likely implies a variation in refinery product water consumption density because of the correlation between energy and water. The variation in refinery product consumption information could shed light on how the preference for different transportation fuels would affect resource consumption and environmental sustainability.

In this study, water consumption was modeled and discussed within the U.S. petroleum refining industry. The amount of water consumption for any specific refinery can vary significantly. Consequently, some "typical" refineries were modeled based on the expected range of water consumption for these facilities. The actual water consumption at any one particular facility will differ from the results given here, but they are representative of the industry on average.

2. Methodology

2.1. Refinery water sources

Refineries can have various water sources. With the goal of addressing the impact of energy production on fresh water supply stress, it is important to identify typical refinery makeup water sources and also to more fully define the scope of "water consumption."

There are several primary water sources for refineries: "fresh" surface water (lakes and rivers) and "fresh" ground water (aquifers). Some refineries can also use surface or ground saline water (sea water and brackish water), for at least some of their needs [13]. Water from aquifers is normally accessed by drilling wells, while surface water is directly pumped out of the water body [16,17]. Previous research effort by Jacobs Consultancy has revealed the actual direct sources of the makeup water of the top 135 U.S. oil refineries [16]. Starting with these results, the present study conducted further research to identify the specific primary water sources for refineries on the basis of crude capacity (normalized to the basis of a barrel of oil based on crude capacity share) for each region of Petroleum Administration for Defense District (PADD), five regions into which the United States can be divided. Once-through water usage (sea or fresh) was excluded in present study due to its small and shrinking usage, and small losses to evaporation. The focus of this study scope is to quantify "fresh" water consumption, which includes (1) surface water (lake or river), (2) city/municipal water, and (3) ground water. About 40% of the water sources (of the total refining capacity, normalized on a barrel basis) for refineries were known; the rest were estimated based on the facility's size and geographic location (e.g., within city limits, in a dry region, on a river or major lake). Based upon this analysis, Table 1 estimates water source shares (on capacity-weighted basis) for the three largest PADDs.

Overall, in the United States, 72% of all water used by refineries in the PADDs comes from rivers or lakes, 10% comes from groundwater, and 18% is city or municipal water (accurate to ± 10%). Compared to shares calculated on number of refineries basis [16], the percentage in Table 1 on crude input capacity basis indicates a greater usage of river/lake water. This is because most of the larger refineries tend to use water directly from a lake or river, while many of the smaller ones utilize at least some city water. City/municipal water is ultimately