Fuel 157 (2015) 292–298

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

A comparative assessment of resource efficiency in petroleum refining

Jeongwoo Han [a,*], Grant S. Forman [b], Amgad Elgowainy [a], Hao Cai [a], Michael Wang [a], Vincent B. DiVita [c]

[a] Systems Assessment Group, Energy Systems Division, Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, IL 60439, United states
[b] Sasol Synfuels International, 900 Threadneedle, Suite 100, Houston, TX 77079, United States
[c] Jacobs Consultancy Inc., 5995 Rogerdale Road, Houston, TX 77072, United States

HIGHLIGHTS

- Investigate refineries with various complexities and operational flexibilities.
- Categorize refineries into three groups by crude density and heavy products yield.
- Estimate GHG emissions cost to produce more of the desirable fuels.
- Complex refineries can process heavier crude into more gasoline and distillate.
- Complex refineries are more resource efficient, but more energy and GHG intensive.

ARTICLE INFO

Article history:
Received 12 January 2015
Received in revised form 4 March 2015
Accepted 10 March 2015
Available online 25 March 2015

Keywords:
Petroleum refinery
Life-cycle analysis
Energy efficiency
Resource efficiency
Greenhouse gas emissions

ABSTRACT

Because of increasing environmental and energy security concerns, a detailed understanding of energy efficiency and greenhouse gas (GHG) emissions in the petroleum refining industry is critical for fair and equitable energy and environmental policies. To date, this has proved challenging due in part to the complex nature and variability within refineries. In an effort to simplify energy and emissions refinery analysis, we delineated LP modeling results from 60 large refineries from the US and EU into broad categories based on crude density (API gravity) and heavy product (HP) yields. Product-specific efficiencies and process fuel shares derived from this study were incorporated in Argonne National Laboratory's GREET life-cycle model, along with regional upstream GHG intensities of crude, natural gas and electricity specific to the US and EU regions. The modeling results suggest that refineries that process relatively heavier crude inputs and have lower yields of HPs generally have lower energy efficiencies and higher GHG emissions than refineries that run lighter crudes with lower yields of HPs. The former types of refineries tend to utilize energy-intensive units which are significant consumers of utilities (heat and electricity) and hydrogen. Among the three groups of refineries studied, the major difference in the energy intensities is due to the amount of purchased natural gas for utilities and hydrogen, while the sum of refinery feed inputs are generally constant. These results highlight the GHG emissions cost a refiner pays to process deep into the barrel to produce more of the desirable fuels with low carbon to hydrogen ratio.

1. Introduction

Increasing concerns with the consequences of climate change turns scrutiny towards the source and efficiency of energy production and consumption. Within this context, petroleum is a major source of global energy demand and a primary component of transportation fuels. In 2011, petroleum accounted for 34% of global energy consumption and 36% of global greenhouse gas (GHG) emissions [1], while the transportation sector in the US and the EU consumed 71% and 62% of total petroleum products, respectively, as shown in Fig. S1 [2,3].

Regulations are being developed in the US and EU to reduce petroleum consumption, encourage use of alternative fuels and promote energy efficiency. In the US, the Renewable Fuel Standard (RFS) mandates the production of 36 billion gallons of renewable fuels with various GHG emissions reduction thresholds relative to conventional gasoline and diesel [4]. California implemented the Low Carbon Fuel Standard (LCFS) in 2009 to reduce the GHG intensity of transportation fuels [5]. The Renewable Energy

* Corresponding author. Tel.: +1 630 262 6519.
E-mail addresses: jhan@anl.gov (J. Han), grant.forman@us.sasol.com (G.S. Forman), aelgowainy@anl.gov (A. Elgowainy), hcai@anl.gov (H. Cai), mqwang@anl.gov (M. Wang), Vince.Divita@jacobs.com (V.B. DiVita).

http://dx.doi.org/10.1016/j.fuel.2015.03.038
0016-2361/

Directive (RED) in the EU requires 10% of transportation energy consumption to be produced from renewable sources by 2020 [6]. The production of energy from these renewable sources must achieve a minimum 35% reduction in life-cycle GHG emissions against conventional, petroleum-derived baseline fuels, with the threshold being elevated to 50% in 2018 [7].

Notably, all of these regulations require a reliable estimation of life-cycle GHG emissions of alternative transportation fuels, including petroleum-derived gasoline and diesel baseline fuels. Among the major stages in the life-cycle of a petroleum fuel (crude recovery, transportation, refining and fuel transportation, distribution and combustion), the largest GHG emissions source is fuel combustion, which can be accurately estimated from the carbon content of the fuel. The next largest GHG emissions source for desirable fuels (e.g., gasoline, diesel and jet) is the petroleum refining stage. Oil refineries process a slate of crude oils of different qualities into multiple fuel products for various applications. In order to accurately estimate variations in petroleum refinery efficiency and GHG emissions, reliable information relating to overall energy inputs and outputs is required for different crude types, refinery configurations and product outputs. In addition, energy inputs and GHG emissions at the refinery level need to be allocated systematically among petroleum products in order to develop accurate product-specific GHG emissions intensities.

Both crude quality and final production specification are key drivers for refinery configuration, operations and ultimately, refining energy efficiency. For example, historically, crude inputs into US refineries have typically been heavier (average API gravity of 30–32°) than EU refineries (average API gravity of 36–37°) [1,8]. In the former case, because crude inputs are heavier, more intensive processing is required to produce gasoline and distillate. In terms of market demands, non-transportation fuel oil demands in the US (Fig. S1) are smaller than in the EU. Consequently, US refineries produce a smaller share of residual fuel oil (RFO) than EU refineries do, and thus are considered to be more resource efficient. Since gasoline and diesel require significantly more processing than heavy products, US refineries in general are more complex and energy-intensive than EU refineries. On this basis, it is unsurprising that US refineries have larger deep conversion units such as cokers and fluidized catalytic crackers (FCC) relative to other regions (Fig. S3). These process units are instrumental in converting heavy refinery intermediate streams into gasoline and diesel and are typically energy-intensive; hence their impacts on refining efficiency and life-cycle analysis GHG emissions can be substantial [9].

Other studies have examined product-specific efficiencies and GHG intensities of refined products and there is a wide variation in the potential emissions due to differences in modeling methodology and input data. Furuholt used data of eight general refining processes in Norwegian refineries to allocate refining energy use and emissions to gasoline and diesel [10]. Similarly, Wang et al. used a detailed process-level approach for a notional refinery and demonstrated the difference between various allocation metrics (energy, market-value and mass) [11]. Recently, Elgowainy and Forman et al. used a refinery Linear Programming (LP) model to simulate operation of 43 large US refineries in order to estimate life-cycle GHG emissions of major petroleum products such as gasoline, diesel and jet fuels [9,12]. By covering 70% of the total US refining capacity, they: (1) developed a correlation between the overall efficiency of US refineries and the corresponding crude quality, refinery complexity and product slate; (2) provided average and variations of product-specific efficiency and process fuel shares for each refined product; and (3) examined the possible impacts relating to changing crude slates, regional and seasonal variation, changing gasoline-to-diesel (G/D) ratios and Gas to Liquid (GTL) diesel blending on refinery and product-specific efficiencies. A recent well-to-wheels study by the Joint Research Centre (JRC) of the European Commission evaluated energy and GHG emissions performance associated with various automotive fuels and powertrains, including petroleum gasoline and diesel. By considering a marginal approach (future reduction in gasoline and diesel demand), JRC concluded that marginal diesel in the EU is more energy- and GHG emission-intensive than marginal gasoline [13]. Other authors have performed individual refinery analyses and incorporated these results into life-cycle analysis (LCA) for multiple notional refinery configurations [14–18].

These studies only focused on a specific region or configurations and considered only a limited range of crude quality and product slates, which is not sufficient to fully understand the complex interaction between crude quality, refinery configuration and yield of gasoline and distillate on one hand, and the consequent life-cycle GHG emissions on the other hand. These disparities between previous studies suggest a need to use a large pool of refinery data to potentially simplify general understanding of refinery GHG emissions. Noting the impact of key refinery metrics such as API gravity and heavy product (HP) yield (e.g., RFO, pet coke and asphalt) could have on refinery efficiency and GHG emissions, we analyzed results from LP modeling of 17 large EU refineries in addition to recently reported 43 US refineries [9,12] and grouped them according to their crude API gravity and HP yields. Note that these two parameters (API gravity and HP yield) were recently identified by Elgowainy et al. [12] as the key parameters that determine a US refinery's overall energy efficiency [9,12]. In this study, API gravity and HP are used to represent resource efficiency. By analyzing data at the sub-process level in these 60 refineries, this study correlates the crude API gravity and HP yields of different groups of refineries with the product-specific energy efficiency for each refinery product and presents previously unavailable life-cycle impacts of refinery resource efficiency on product-specific and refinery-level GHG emissions. The life-cycle analysis of petroleum fuels from various refineries was facilitated using Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET™) model [19]. The GHG emissions calculation combines carbon dioxide, methane and nitrous oxide with their global warming potentials, which are 1, 25 and 298, respectively, as recommended by the latest Intergovernmental Panel on Climate Change for a 100-year time horizon [20].

2. Refinery modeling and analysis approach

In the current study, refinery LP modeling was employed to simulate and compare the operations of 43 US and 17 EU refineries with individual processing capacity of over 100,000 bbl/day crude oil. Note that although the 17 EU refineries account for only 25% of the total EU refining capacity, their operational characteristics appear to be quite consistent with aggregate average EU refinery operations (see Table S1).

The selected US refineries were located in Petroleum Administration for Defense Districts (PADDs) 1, 2, 3 and 5, while the selected EU refineries were located in the coastal regions of Europe. Refinery LP models typically maximize profit by determining the optimal volumetric throughput and utility balance among various process units within a refinery under specific market and operation conditions [21]. The output files from LP model simulations contain volumetric and mass flow rates associated with inputs and outputs of process units. Using this information, energy inputs and outputs can be calculated by using known heating values of various stream components.

In this study, we grouped the U.S and EU refineries described above into three different groups according to their average crude API gravity and HP yield. As shown in Fig. 1, refineries were