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Energy efficiency improvements in the U.S. petroleum refining industry

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Abstract

Energy efficiency improvements can be a cost effective approach for reducing energy consumption and CO_2 emissions. However, estimating the cost and potential for energy efficiency improvements in the U.S. petroleum refining industry is complex due to the diversity of U.S. refineries and lack of publically available detailed process performance data. A notional aggregate model of the U.S. petroleum refining sector was developed, consisting of twelve integrated processing units, steam generation, hydrogen production, and water utilities. The model is carbon and energy balanced such that crude oil inputs and major refinery sector fuel outputs are benchmarked to 2010 data. Current penetration of efficiency measures are estimated to benchmark energy estimates to those reported in U.S. Department of Energy (U.S. DOE) 2010 data. Each measure's remaining energy savings potential is estimated and their costs are compared to U.S. DOE fuel prices. Resulting efficiency opportunities are presented on a cost of conserved energy supply curve.

Roughly 1,200 PJ per year of primary fuels savings (40 % reduction in fuel consumption) and 400 GWh per year of electricity savings (2 % reduction in electricity consumption), representing nearly 70 Mt CO_2 emissions, are potentially cost-effective. An additional 450 PJ per year of primary fuels savings and close to 1,850 GWh per year of electricity savings, representing roughly 26 Mt CO_2 emissions, are not cost-effective.

The model also has the potential to be used to examine the costs and benefits of the other CO_2 mitigation options, such as combined heat and power (CHP), carbon capture, and the potential introduction of biomass feedstocks, which are recommended for further research and analysis.

Introduction

An Energy Star® report prepared for the U.S. Environmental Protection Agency (U.S. EPA) concluded that: "Further research on the economics of energy-efficiency measures, as well as the applicability of these to individual refineries, is needed to assess the feasibility of implementation of selected technologies at individual plants" [Worrell 2005]. However, a robust methodology for estimating the cost and potential for U.S. refinery energy efficiency improvements is complicated by a number of issues unique to refining [Gary 2007, Worrell 2005]. The refining industry is diverse with refineries distributed across the U.S., each having evolved independently to handle changing crude oil inputs and product outputs. The last U.S. green-field refinery was commissioned in 1979, and the average age of the existing refinery fleet is well over fifty years old. However, the existing fleet is not obsolete. Although capacity at individual refineries has increased over time and refineries are continuously being expanded and modernized, no two refineries are ever exactly the same. Each refinery utilizes technologies of different vintage and make, and at any moment in time, there exist a distribution in refinery performance in regards to product yields and energy efficiency. Lastly, individual refinery process performance data is proprietary and rarely publicly available.

The U.S. Department of Energy's Energy Efficiency and Renewable Energy Program's Advanced Manufacturing Office (previously the Industrial Technologies Program) has sponsored a series of energy efficiency potential bandwidth reports specific to energy intensive U.S. industries. Despite the refinery industry complexities, an initial U.S. petroleum refinery bandwidth report focused on five of the most energy intensive refinery unit operations concluding that 27 % of refinery energy consumption could be reduced through adoption of best practices and state-of-the-art (SOA) technologies [Energetics, 2006]. A recent update covers the whole refinery industry concluding that 13 % of total refining energy consumption could be reduced by implementing best practices and SOA technologies and then an additional 25 % reduction is conceivably possible through the adoption of R&D technologies currently under development [Energetics, 2013]. Costs associated with achieving these potentials where not addressed in either report.

A recent Lawrence Berkeley National Laboratory (LBNL) report helps address the complexity of the refinery industry and need for further research on the economics of efficiency measures [Morrow, et. al., 2013]. This research had three primary objectives: 1) develop robust methods for estimating refinery process performance, energy requirements, CO_2 emissions, and costs of energy efficiency measures applicable to petroleum refining in the U.S.; 2) establish representative baseline data of production, energy, CO_2 emissions and costs; and 3) generate cost of conserved energy supply curves to estimate cost effective energy efficiency potential. The complexity of assessing the feasibility of implementation of selected technologies at individual plants is reduced by modeling the whole U.S. refinery industry in aggregate. A notional model for a generic U.S. refinery was developed and "tuned" to reflect U.S. aggregate yield and energy consumption data based on literature reviews and private sources spanning the period from 1975 to the present.

This conference paper presents a condensed version of that analysis with an overview of the methods, baseline estimates, and the resulting aggregated U.S. petroleum refinery industry cost of conserved energy supply curve and cost-effectiveness ranges based on U.S. DOE's, Eenergy Information Administration's industrial sector natural gas price forecasts [EIA 2014] and converted to Euros at a conversion of 0.73 EUR per USD [XE.com 2014].

Methods

Petroleum refineries consist of a complex interconnected set of processing units integrated through the flow of process streams (*i.e.* the molecules of interest, such as hydrocarbons, hydrogen, and contaminants) and various utility streams (*i.e.* carriers of energy, such as fuel, steam, cooling water, and electricity). Therefore, all processes and their interactions must be taken into account when considering efficiency improvements. Further, one can speak of the efficiency of a process, not only in terms energy, but also in terms of mass and information. While these three efficiencies are distinct they are also highly correlated. Improved mass efficiency will improve energy efficiency, and the collection and transmission of data enables process optimization and control to be used to improve both. Therefore, to systematically describe and quantify the efficiency options that might be considered within a refinery, these measures can be categorized based on the level at which they are implemented in the refinery and by whether they directly impact the flow of mass, energy, or information through the refinery.

Due to the highly integrated nature of the petroleum refinery, energy abatement measures will not be additive in general. A hierarchy of improvements exists, such that initial improvements limit the effectiveness of later improvements. Refineries are unique relative to most industrial facilities as they are self-sustaining for much of their fuel and electricity use. Most processing steps in the refining of crude oil into finished products produce fuel by-products, most notably fuel gas and catalyst coke, which are consumed within the refinery to supply heat and generate electricity. Therefore, reducing fuel consumption is not necessarily cost effective, if it is not matched with a reduction in fuel gas generation. If this caveat is over looked then efficiency potentials could be overestimated. Simply improving efficiency without corresponding reductions in fuel gas generation could result in excess fuel gas and catalyst coke potentially requiring additional investments in combined heat and power generation systems to utilize these excess fuels.

Detailed information on the performance of individual petroleum refineries is generally not available at the process level, making it difficult to ascertain the current, and more importantly, the future state of the industry in regards to energy usage and emissions. Therefore, twelve core processes that dominate energy consumption within the U.S. refinery industry are modeled in a notional generic refinery. Figure 1 is an overall process block flow diagram showing the major hydrocarbon flows between the twelve unit processes evaluated in the analysis shown in Figure 1.

Each of the twelve units are mostly comprised of process equipment such as feed pumps, heaters, reactors, separators, heat exchangers, and compressors, all integrated through piping, instrumentation, and controls. The process feed stream is conveyed to the unit using a feed pump, and is then heated to the desired reaction temperature in a fired heater, before being fed to a reactor. In addition to this petroleum feed, a recycle gas is also co-fed to the reactor. The product from the reactor is cooled in a heat exchanger and separated into gaseous and liquid products, with the liquid hydrocarbon product being sent either to finished product blending or on to further processing steps. The overhead gas is typically purged of impurities, re-compressed, and recycled back to the reactor to be re-used in the chemical reactions. Additional make-up gas may also be required. Control valves are used throughout to maintain the desired flow rates of the streams within the process.

Thermodynamic and chemical kinetic considerations establish pressures and temperatures required to maximize the yield of desirable product(s). Based on these pressure and temperature conditions, and estimated stream physical properties and flow rates, a heat exchanger network (HEN) is designed around the reactor and separation operations to provide required heating or cooling. An energy efficient design will recover heat from hot process streams that require cooling and transfer it to cold process streams that require heating. The operating pressure requirements for the reactor and separations, along with estimates of pressure drops through all equipment (reactors, separators and heat exchangers) and piping establish pumping requirements for liquid streams and compression requirements for vapor streams. Almost all refinery processes are designed to operate continuously requiring a robust process control system for smooth and stable operations.

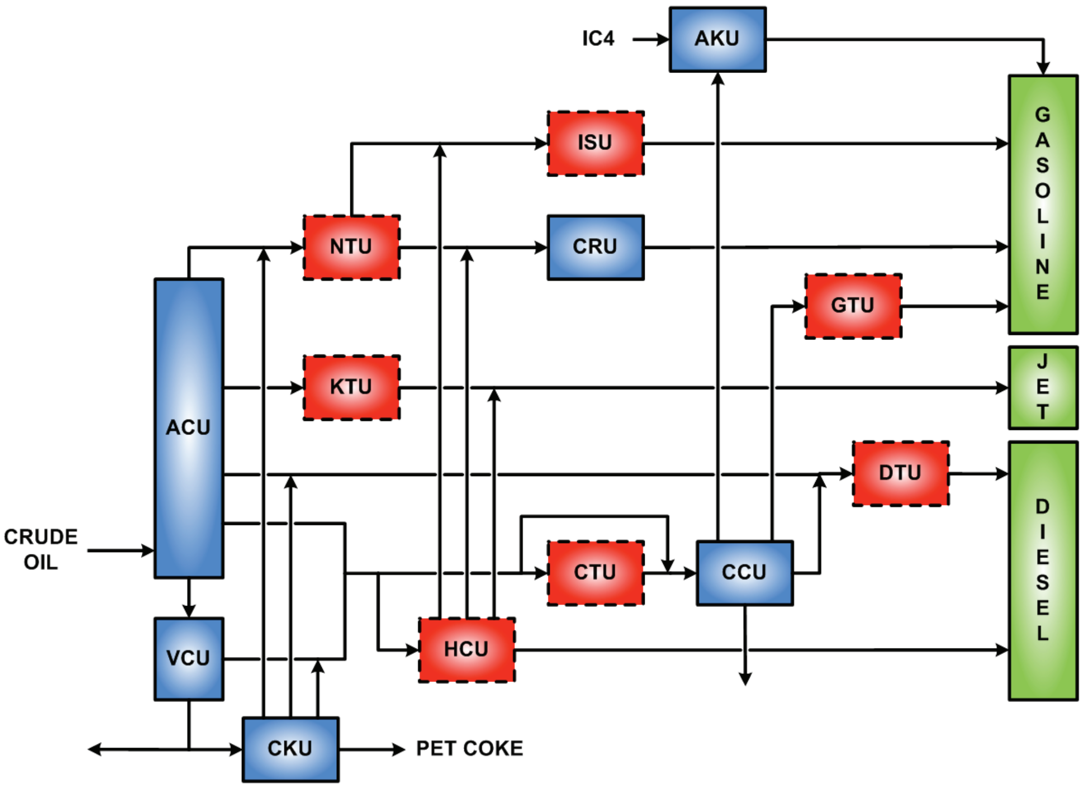

Figure 1. Overall Process Block Flow Diagram (dashed lines denotes H_2 consuming unit processes).
Processing units or systems:

- *CDU Crude Distillation Unit*
- *ACU Atmospheric Crude Unit*
- *VCU Vacuum Crude Unit*
- *CKU Coking Unit*
- *CTU Cat-Feed Treating Unit*
- *CCU Catalytic Cracking Unit*
- *HCU Hydrocracking Unit*
- *DTU Diesel Treating Unit*
- *KTU Kerosene Treating Unit*
- *NTU Naphtha Treating Unit*
- *CRU Catalytic Reforming Unit*
- *ISU Isomerization Unit*
- *GTU Gasoline Treating Unit*
- *AKU Alkylation Unit*
- *RGS* Refinery Gas Processing & Flare Systems*
- *HYS* Hydrogen Production & Recovery Systems*
- *AGS* Acid Gas Removal & Sulfur Recovery Systems*
- *SPS* Steam & Power Systems*
- *WTS* Water Treatment & Delivery Systems*

** Additional units or systems considered "off-site", as defined in the text, and therefore not shown.*

Additionally, refinery "off-site" (e.g., utilities such as steam and electricity generation, and hydrogen production) contribute to refinery industry energy consumption and in this analysis their energy consumption is allocated to the twelve processing units shown in Figure 1. The allocation method is based on the energy (i.e., fuel, steam, electricity, etc.), as well as the hydrogen and gas processing requirements of each processing unit. Where steam or hydrogen is utilized in processing units, fuel and electricity requirements for steam generation and hydrogen production are assigned to the individual units according to their proportion to the total steam and hydrogen production of the entire refinery. For each processing unit, fuel and electricity consumption can be direct (e.g., fired heaters and pumps) which is designated "inside the battery limits" (ISBL) for the unit, or fuel and electricity consumption can be indirect (e.g., steam and hydrogen) which is designated "outside the battery limits" (OSBL).

To estimate the aggregate energy consumption and performance of the twelve units, required modelling parameters, when not available in the open literature, were deduced by reverse engineering, starting from reported aggregate data, or inferred from descriptive accounts of past, current and future technologies. Models coupling empirical data and engineering calculations for U.S. refinery processes were developed for the LBNL study, allowing the complexity of U.S. refineries and the impact of process integration on overall refining efficiency to be assessed. The refinery models are constrained to satisfy a U.S. aggregated product demand slate (e.g., quantity of gasoline, diesel, jet fuel, etc.) using a composite crude oil assay representative of the average crude oil composition processed in the U.S.. The refinery models are carbon balanced allowing carbon to be tracked and CO_2 emissions estimated as fuels are consumed throughout the refinery processes.

The cost of conserved energy (CCE) for an energy efficiency measures is calculated with the following equation:

$$CCE = \frac{I \times q + (M - B)}{ES} \quad (1)$$

where:

- *CCE* Cost of conserved energy, €/GJ
- *I* *Added* capital cost, €
- *q* Capital recovery factor, yr^{-1}
- *M* Non-energy annual increases in O&M costs, €
- *B* Annual decreases in O&M costs due to non-energy productivity improvements, €
- *ES* Annual energy savings, GJ/yr

Assigning capital costs to the energy efficiency measures described can be problematic, even when the cost of any new equipment is known, since energy efficiency projects involve modifications to an existing plant. This is especially true when considering major process modifications, such as improved heat integration. Several items must be known in order to make this estimate: the number and character of the new equipment to be added, the added cost of the equipment, and the added cost of installation. The first item may be difficult to estimate if some of the existing equipment is to be re-used. The last item is particularly tricky for projects that involve re-working an existing process. Examples of these types of projects are heat integration and piping network modifications.

The capital recovery factor of 17.1 % was assumed for the analysis. The capital recover factor is used to convert unit capital costs to cost per unit energy savings (e.g., €/GJ) for energy efficiency measures.

Any given energy measure applied may result either in increases, decreases or both in annual non-energy operating and maintenance (O&M) costs. Many of the measures to reduce fuel requirements also result in decreases or increases in electricity usage; however, the value of incremental changes in electricity purchases are excluded from the CCE calculation. Other increases in O&M considered result from additional costs associated with improved catalysts and other process consumables.

In addition to measures that bare directly on unit-process fuel and electricity usage, (e.g., furnace efficiency or process pumping efficiency improvements) or indirectly (e.g., steam utilization improvements), measures solely affecting energy usage of major refinery offsites (e.g., boiler efficiency improvements) have been allocated to each unit process based on a weighted distribution of unit consumption of total offsite energy generation. This procedure allows composite fuel and electricity-usage abatement curves to be generated by simply adding together the individual unit-process curves. Measures are selected for their impact on fuel energy conservation but in many cases, they also have an effect (either decreasing or increasing) on electricity usage. Therefore, electricity impacts are included in the fuel conservation supply curves by converting electricity (e.g., kWh) to fuel energy (e.g. joules) using a conversion factor (1 kWh = 3.6 MJ). However, this excludes the fuel used to generate electricity and is intended to reflect final energy consumption within the petroleum refining industry. CO_2 emissions are calculated using the IPCC natural gas conversion factor of 0.0561 Mt CO_2/PJ [IPCC 2006]. It is assumed that the marginal electricity consumption within the petroleum refinery industry is grid purchased electricity. A 2010 U.S. average CO_2 emissions factor of 0.572 Mt CO_2/TWh is used to convert electricity saving into grid level CO_2 emissions[1].

An algorithm is used to order the CCE values from lowest to highest begins with a base case representation of a refinery that has not implemented any of the energy measures identified. The algorithm then examines all of these measures separately and selects the measure with the lowest cost of conserved energy. This becomes the basis for the next iteration and the procedure is repeated until all of the measures have been accounted for. This methodology implicitly accounts for changes in the cost of conserved energy for any specific measure due to the implementation of measures selected earlier in the sequence.

Results

Table 1 presents estimated energy consumption for the twelve modelled unit processes for the year 2010. This estimate is based on 2010 process throughput [EIA 2013], and engineering modelling of energy required to produce the 2010 U.S. petroleum refinery aggregated output product slate (i.e., gasoline, diesel, jet fuel, etc.). In addition, the energy (fuels, steam, and electricity), energy associated water-usage (process, cooling, and waste) and hydrogen production are also modelled.

Each unit process presented in Table 1 was analyzed separately to qualify and quantify potential energy efficiency measures. The U.S. petroleum refinery industry is first modelled without energy efficiency (i.e., vintage 1995) and current penetration rates are estimated to reflect 2010 aggregate energy consumption (shown in Table 2). The remaining potential is evaluated as described in the methods description above. Figure 2 presents the resulting aggregate cost of conserved energy supply curve for the U.S. petroleum refining industry.

Many of the energy efficiency and abatement measures are similar in that they affect common equipment used throughout the processes (e.g., process heaters and boilers, heat exchanges, pumps, steam distribution, etc.) although their application within individual process units varies. However, the application of many of the measures within the processing units has different costs and therefore summing them across the whole notional refinery, and averaging their cost would misrepresent costs by averaging higher and lower cost measures. Instead, measures from each of the processes are presented as individual

1. This is calculated from 2,270 Mt CO_2 of electricity sector emissions associated with 3,971 TWh of electricity production reported in EIA AEO 2012 [EIA, 2012].

Table 1. Estimated Energy Consumption for the U.S. Petroleum Refining Model circa 2010.

Process	Throughput	Fuel (PJ, Primary)		Electricity (GWh, Final)	
	Million bbl/year	ISBL	OSBL	ISBL	OSBL
CDU	5,540	399	638	4,048	1,769
CKU	725	107	26	2,246	868
CTU	1,081	48	392	143	2,076
CCU	725	-335	42	2,305	2,081
HCU	474	92	471	61	2,251
DTU	1,033	51	243	150	1,225
KTU	575	29	53	401	376
NTU	1,213	103	100	176	423
CRU	992	313	119	979	1,507
ISU	147	6	28	21	9
GTU	419	34	136	60	423
AKU	170	0	35	4	500
Total Modeled Energy Consumption		848	2,283	10,596	13,507

measures in Figure 2. This results in an accurate representation of costs and impacts.

It has been suggested in the past that in modern petroleum refineries, the "low-hanging fruit" efficiency improvements have been accomplished [CONCAWE 2008]; while others disagree [Laitner, 2012]. The results of this analysis indicate that roughly 1,200 PJ of annual energy savings are still to be achieved below a fuel price of €5.8/GJ.

Total fuel, electricity and CO_2 emission reduction potentials are shown in Table 2. The negative electricity savings within the Potentially Cost Effective category in Table 2 result when fuels savings measures are replaced with electricity consuming measures. An example of this is replacing recycle compressor steam-drives with electric drives, the largest of which take place in the NTU (Naphtha hydrotreating unit). Replacing steam drives reduces steam loads and therefore fuel consumption for steam generation, but introduces a new electricity load. Because many of these fuel reduction measures are cost effective to implement the cumulative electricity effects result in a net increase in electricity consumption within this category of cost-effective measures. The top ten energy savings measures are presented in Table 3 along with their respective fuel and electricity savings potential, the major processing units they're applied to, and their cost of conserved fuel.

Discussion

In this analysis, cost of conserved energy supply curves have been developed for the U.S. petroleum refining industry. A bottom-up, predictive approach was employed to estimate energy usage on an refinery processing unit basis. This approach builds upon earlier efforts focusing on energy efficiency technologies [Worrell et. al. 2005], or establishing energy-consumption baselines and efficiency potentials [Energetics 2006, 2007, 2013], by quantifying potential benefits and costs of energy efficiency improvement measures applied to specific refinery process units. Twelve primary refinery process units were modeled and saving associated with supporting processes, such as gas processing, hydrogen production, steam and power systems, acid gas removal and water treatment have been allocated to the twelve units based on utilization. Individual processing unit cost of conserved energy supply curves are discussed in a previous LBNL report [Morrow, et. al. 2013].

The tools developed for the current analysis include an aggregate, notional petroleum refinery model that is mass and energy balanced, and an accounting methodology that tracks the inter-dependent nature of adopting energy-efficiency measures within a highly integrated industry. Importantly, these tools are designed such that they can, with some modifications, be used to analyze other national or regional refining industries; as well as, the petrochemical industry, which is similarly integrated. Scenarios can be examined that specifically look forward in time at a range of market and policy driven changes in the transportation industry affecting energy requirements and efficiency adoptions within the petroleum refinery industry.

The primary application for the cost curves can be for inclusion in integrated assessment models (IAM), which require accurate bottom-up representation of energy efficiency technologies; otherwise, it will be difficult to estimate with confidence, the costs and benefits of reducing GHG emissions by adopting industry-based efficiency standards. The baseline information, cost curve data and models developed in this analysis can have other applications. The lists of energy efficiency measures developed provide a database of potential cost-effective measures that can be taken by industry to improve their energy efficiency and to mitigate GHG emissions. The refinery model developed is general and has the potential to be used to explore the benefits and costs of other GHG mitigation options. For example, the

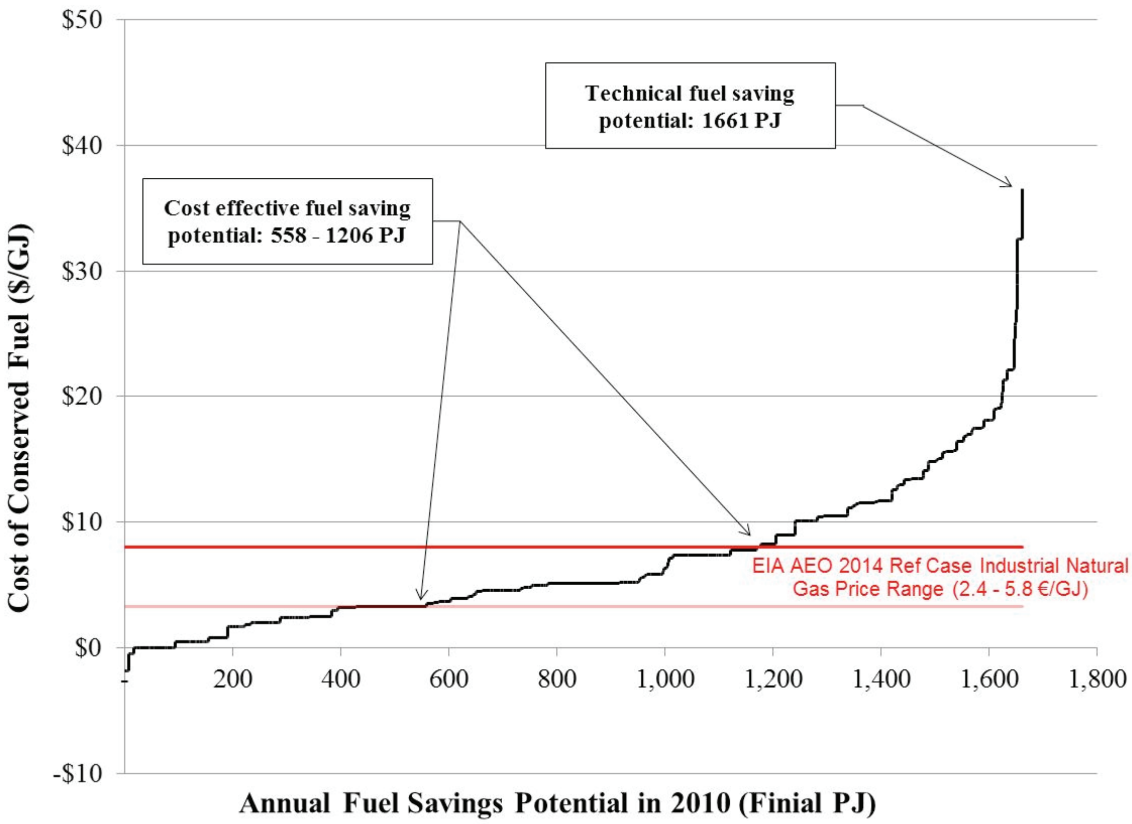

Figure 2. Cost of Conserved Energy Supply Curve (includes fuel & electricity).

Table 2. Cumulative results.

	Fuel Savings (PJ/yr)	Electricity Savings (GWh/yr)	CO_2 Emissions Reductions (Million t CO_2/yr)†
Cost Effective *	556	651	32
Potentially Cost Effective **	649	-240	36
Technical but not Cost Effective	448	1,844	26
Total	1,653	2,255	94

** Cost Effective = the cumulative totals that fall below the lower price line in Figure 2.*

*** Potentially Cost Effective = the cumulative totals that fall in between the lower and higher price lines in Figure 2.*

† Fuel CO_2 emissions are based on the IPCC conversion factor of 0.0561 Million t CO_2/PJ [IPCC, 2006], and 0.586 Million t CO_2/TWh for the U.S. electric grid in 2010 [EIA, 2012].

Table 3. Top energy savings measures.

Energy Savings Measures	Processing Unit	Fuel Savings (PJ/yr)	Electricity Savings (GWh/yr)	Cost of Conserved Energy (€/GJ)
Install HRSG Post Regenerator	CCU	132	0	€3.74
Install Overhead Vacuum Pump	CDU	129	0	€2.41
Install Furnace Air Pre-Heat	CDU	49	0	€5.63
Install Overhead Chillers	CDU	44	143	€7.62
Revamp Heat Integration (low-cost)	CDU	40	172	€1.78
Improve catalysts to reduce H2 consumption	HCU	36	31	€5.38
Add Recycle & ST Ejector	CDU	36	0	€0.55
Install New Internals	ACU	34	161	€6.55
Reduce Coking of Tube Surfaces	CDU	34	0	€2.32
Efficient Burners/Control X Air	CDU	32	0	€2.84
Install Furnace Air Pre-Heat	CRU	30	0	€8.40

model framework is capable of examining the impact of introducing renewable fuels on the cost and emissions from petroleum refining, and the cost and effectiveness of future carbon capture technologies in a petroleum refinery setting. While this capability has not been modeled explicitly for this body of analysis, adding this capability would be an incremental addition to the core model framework.

The current analysis does not consider the ramifications of current trends in petroleum refining related to novel technologies, crude oil qualities, fuel specifications, and product slates. These trends will have a significant impact on the future path of the U.S. refining industry. Future challenges that will likely affect the industry include: lower gasoline-to-distillate product ratios due to ethanol blending into gasoline, vehicle hybridization, and projected demand growth for jet and diesel fuel; internationally agreed to marine SO_x reductions requiring low-sulfur bunker fuels; refinery crude slate changes due to increased production of domestic shale oils, and increased imports of Canadian synthetic crude oils and dilbit blends; and further implementation of renewable and/or low-carbon fuel standards, which may introduce truly "drop-in" biofuels in the long term. Future sensitivity analyses will be needed to examine impacts of these potential changes, since many of these could have negative ramifications for improving efficiency and lowering emissions, while some may be positive. The role of CO_2 capture and sequestration in petroleum refining will also need to be examined more completely if CO_2 emissions are to be drastically reduced over the next fifty years.

In closing, the analysis presented here is unique in that it provides a rigorous framework for evaluating energy consumption and efficiency improvement opportunities within the U.S. petroleum refining industry that previously was not obtainable by looking at reported data alone. The tools developed for this analysis are predictive, meaning that the energy usages are calculated using a bottom-up approach, rather than assumed or derived empirically, and model the individual processing units and ancillary equipment (i.e. hydrogen production, steam, and cooling water) at a level of detail required for quantifying energy efficiency impacts and costs.

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