LIQUID FUELS MARKET MODEL COMPONENT DESIGN REPORT

Prepared for

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Executive Summary

This document presents a proposal for a new model to replace the Petroleum Market Model (PMM) currently used in the National Energy Modeling System (NEMS) by the Energy Information Administration of the Department of Energy. The new Liquid Fuels Market Module (LFMM) prototype proposed here will incorporate some of the same model structure and use similar data inputs as the PMM, but with modifications and additions to reflect more current liquid fuel market trends. Like the current PMM, the proposed LFMM will incorporate a linear programming structure to model petroleum-based fuels production – both a model block diagram and general equation sets are provided in this documentation for the prototype. The inputs to the model (both NEMS and exogenous) as well as desired outputs from the model (projections of liquid fuel production costs, petroleum and alternative fuels supplies, refinery energy consumption, refinery and alternative fuel plant capacity and utilization, capacity additions and retirements) are also very similar to those of the current PMM. However, in the proposed LFMM some key differences stand out:

1. Regional breakout: The LFMM will have the flexibility to go beyond the PADD level regions used in the PMM to more accurately reflect current regional distinctions in refinery characteristics. For example, PADD 2 could be broken down into two regions to distinguish those that do and/or will likely have access to Canadian crude from those that do not. Furthermore, PADD 5 could be combined with PADD 4 with the exception of California, which would be its own region due to the distinctive complex nature of refining and crude sources in that State. In addition, an offshore region (Eastern Canada/Caribbean) could be added in the LFMM.

2. Refinery aggregation: The LFMM will provide increased flexibility in modeling refinery configurations. The PMM currently models two refineries (marginal and complex). The LFMM will have the flexibility to model varying numbers of refinery types (e.g., topping, hydroskimming, cracking, and coking).

3. Calibration: The LFMM will incorporate an iterative calibration procedure that will refine technical coefficients in the model to adjust for recent historical refining outputs (e.g., product volumes, prices).

4. The prototype LFMM will be constructed and tested for the capability to incorporate and analyze a wide variety of policy and regulatory cases in a straightforward and transparent manner.

5. Modeling platform: The prototype LFMM will employ the GAMS modeling platform, although the decision for the modeling platform of the final LFMM model is undecided at this point.

In addition to these major changes, one of the over-arching goals of the LFMM is to create a model that is more robust, more transparent, and more accessible to more modelers than the current PMM. A significant challenge in the prototype development, therefore, is to adhere to this goal without undue sacrificing of accurate representation of liquid fuels market dynamics.

Finally, there are several approaches currently used in the PMM that will not be fundamentally changed in the prototype development. These include aspects of the alternative fuels modeling, the international component (e.g., the use of import product supply curves), and the capacity planning algorithm. Further improvements in these areas will be done at a later stage for the final LFMM model.

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1. Overview

Petroleum liquid fuels currently represent the largest source of U.S. energy consumption, accounting for about 37 percent of the total energy mix. Liquid fuels represent 95 percent of transportation energy demand and provide 42 percent of industrial, 15 percent of residential and 1 percent of electricity generation energy needs. Future regulations, legislation or policies that affect the domestic liquids fuels market can significantly affect the level of petroleum imports as well as emissions, both of which are key concerns for U.S. policymakers.

The Office of Integrated Analysis and Forecasting (OIAF) in the Energy Information Administration (EIA) of the Department of Energy (DOE) has undertaken an effort to develop a new Liquid Fuels Market Module (LFMM) to support its ongoing energy projection[1] activities and special requests for supplemental analysis of emerging energy-related policy issues, proposed legislation, and regulations. The LFMM will replace and improve upon the current Petroleum Market Model (PMM), which supports the petroleum conversion and marketing activities of EIA's energy-economy projection system.

EIA provides an annual Reference case projection along with approximately 30 additional cases in its *Annual Energy Outlook*, which estimates the impact of alternative economic growth, world oil prices, technology, and policy assumptions on U.S. energy markets. The EIA projections and analyses are developed using the National Energy Modeling System (NEMS).

NEMS is a computer-based, energy-economy modeling system that simulates production, imports, conversion, consumption, and prices of energy. Its projections are subject to assumptions on macroeconomic and financial factors, world energy markets, resource availability and costs, behavioral and technological choice criteria, cost and performance characteristics of energy technologies, and demographics. The system is designed to represent the important interactions of supply and demand in U.S. energy markets. See http://www.eia.doe.gov/oiaf/aeo/overview/index.html for a more complete overview of the National Energy Modeling System.

The role of petroleum, refining, and alternative liquid fuels in the U.S. energy market is currently analyzed through the PMM. The PMM consists of regional refinery linear programming (LP) models with two distinct refinery categories modeled in each region. The refinery models incorporate technologies and economics associated with the transformation of available crude oil and other inputs to consumer energy products. The PMM solves for liquid fuel prices, crude oil and product import activity, domestic refinery capacity expansion, and fuel consumption. The solution provides projections for the demand for liquid fuels, incorporating the prices of raw

[1] From EIA's perspective, projections are unconditional statements about what the future will be whereas projections are "highly conditioned" statements about the future. For example, the EIA reference case always assumes that current laws and regulations will not change. If the past is prologue, we know that laws and regulations will change and therefore at least some of the conclusions will be wrong. The EIA reference case cannot be an accurate projection of the future. The EIA reference case is a baseline against which the impact of proposed policies, laws, and regulations can be estimated.

material inputs, imported liquid fuels, capital investment, as well as the domestic production of crude oil, natural gas liquids, and other unconventional refinery inputs.

The PMM has been in place for some time, and has undergone a number of fixes and adjustments to adapt to changing environments and advances in technology. These changes have led to increased model complexity and the need for user constraints. The module also suffers from some of the over-optimization limitations inherent in complex LP modeling systems.

This component design report (CDR) provides an overview of the PMM and its shortcomings. It also proposes a series of options to mitigate these shortcomings, improve upon the module's ability to address emerging energy markets and policies, and improve upon the interface with other modules and sectors of NEMS. The primary focus of the CDR is on the regional refining LP representations that constitute the primary component of the PMM and LFMM product supply and price projection functions.

Linear programming appears to offer the most appropriate and widely-accepted approach to the analysis of the refining and conversion of crude oil and other inputs to satisfy the domestic demand for liquid fuels. It provides the framework for incorporating interrelated technologies, diverse feed and product qualities, and economic factors that will establish refined product production, prices, and margins. Use of the refinery LP also provides a wide range of flexibility for adapting to changing environments, policy initiatives, and emerging technologies.

While the LP model is accepted as an appropriate approach to refining and liquid fuel market analyses, it has a number of potential drawbacks. LP models can become overly complex and subject to over-optimization, which can lead to implausible results. The current PMM, which has evolved over time with layers of modifications, has become overly complex and less transparent. It suffers from a simplistic linkage to the international liquids fuels market, and is subject to the over-optimization limitations of LP systems. It has also encountered difficulties in developing reasonable price differentials and margins, and in representing fuel, crude and product imports, and refinery expansion. Maintaining and operating the existing PMM has also become costly and time-consuming.

In addition to resolving the shortcomings of the PMM, the LFMM also needs to be more adaptable to current and anticipated market environments, future energy policies, and emerging technologies and fuel alternatives. World energy markets have evolved significantly over the past 15 years. Liquid fuels are less reliant on traditional petroleum-based products, and petroleum markets are shifting from long-term growth to demand stabilization, even reduction, while the mix of product demand is changing as well.

The potential liquid fuels module of NEMS must expand its coverage of fuel alternatives and adapt to new environments, while maintaining a manageable balance between model detail and flexibility/transparency. The model must be capable of projecting realistic product prices, margins, and liquid fuel balances. It must also account for an environment of domestic industry contraction, increased biofuels and alternative fuels penetrations, new technology developments, and energy policy focused on the goals of addressing climate change.

The remainder of this CDR addresses specific shortcomings of the PMM, makes recommendations on how to address them in the new LFMM, and outlines specific approaches for the LFMM structure. The CDR also provides recommendations for improvements in the interface with other NEMS modules, particularly the international product market. The CDR does not make specific recommendations regarding the International Energy Module, but does propose options for revising the representation of refined product import activities.

2. Statement of LFMM Model Purpose

The Office of Integrated Analysis and Forecasting (OIAF) in the Energy Information Administration (EIA) of the Department of Energy (DOE) has undertaken a project to develop a new Liquid Fuel Market Module (LFMM). The LFMM will replace and improve upon the current Petroleum Market Model (PMM) of the National Energy Modeling System (NEMS) and its combination of sub-modules that also produce liquids like coal-to-liquids (CTL), gas-to-liquids (GTL), and various biomass transport liquids.

Overview of LFMM Purpose

The primary purpose of the LFMM is to support the liquid fuel production, consumption and price activities of NEMS by:

- Projecting petroleum product, crude oil, and product import prices
- Projecting domestic refinery, blending, and product transport operations
- Projecting capacity expansion, refinery gain, and fuel-specific consumption at domestic refineries
- Providing a complete energy balance among:
    - Energy inputs and outputs in the refinery process
    - Energy losses
    - Carbon dioxide emissions resulting from refinery operations

U.S. end-use prices will include the marginal production costs of each product plus markups representing the costs of product marketing, importing, transportation, distribution, and dispensing, as well as applicable State and Federal taxes and any applicable taxes or credits from special regulatory programs. Moreover, the LFMM will be fully and seamlessly integrated within NEMS as part of the solution algorithm to derive a year-by-year energy-economy market equilibrium. It shall continue to receive the needed inputs from the other modules of NEMS and provide the liquids information needed by those modules.

In addition to projection activities, EIA also utilizes NEMS to respond to requests for analysis of legislative, regulation, or other changes. The analyses include examination of issues impacting petroleum products and/or refining. The desired outputs from NEMS and/or the LFMM are similar to those highlighted above, but the special analyses will often focus on specific refining and liquid fuels areas of output, e.g., capacity and investment requirements, specific product price impacts, short term supply/demand, etc. The LFMM will provide the capability within NEMS, or as a standalone refinery modeling system, to simulate aggregate refining operations and to quantify impacts of policies on prices, refinery margins, investments and crude and product imports.

LFMM Capabilities within NEMS

World energy markets have evolved and changed significantly in the past 15 years. Current refining and petroleum product markets are considerably different from those that were characteristic of the era when the PMM was developed. Markets will continue to change in view of issues such as penetration of non-petroleum renewable liquids, efficiency developments, and emphasis on climate change and carbon emissions. Not only will these changes alter the makeup of refining and refined product markets, they will also impact the primary economic and technology drivers of petroleum supply/demand and prices that the LFMM is designed to project.

The LFMM must be designed with sufficient policy levers to allow a broad range of policy analysis related to the liquids market, including:

- Analysis of policies related to the introduction of new technologies, fuels, and fuel specifications
- Expansion of biofuels production and technology representation, and incorporation of biofuels into the liquid fuel market
- Carbon control, environmental policies (e.g., cap-and-trade and MARPOL), or other tax and credit policies, including mandates (such as the Renewable Fuels Standard)
- Option to run and analyze a Low Carbon Fuel Standard (LCFS), patterned after the California LCFS, at the Census Division or national level

The LFMM must also be capable of recognizing the implications of major changes in petroleum markets, such as shifts in product mix, declining gasoline demand, reduced utilization and refining rationalization, and the changing makeup of feedstock (crude or other inputs). In addition, the LFMM must have the capability to adequately represent the interactions with the international crude and refined products market and other liquids energy supply modules within NEMS.

Model Design Considerations

Maintaining and operating the existing PMM has become costly and time consuming. Without constraining the model, it is difficult to develop reasonable projections of prices, margins, fuel consumption, crude and product imports, and refinery expansions. These deficiencies are related to overly complex refinery representations have expanded the PMM with layers of updates and adjustments over time. The expanded model formulation reduces its transparency and increases the opportunity for over optimization. Some of the model proliferations were the result of the need to expand refining technology within the existing model structure, while others were related to incorporation of activities with minimal relevance to liquid fuel production and economics. For example, incorporation of multiple competing processing technologies and secondary petrochemical production activities can add significantly to complexity but will have limited impact on the liquid fuel balance and economics. The products of these activities are critical to the liquid fuel market, but not their technologies and feed. However, it should be noted that such complexity may be deemed necessary for other uses of the LFMM and NEMS. For example, NEMS is often used for activities such as Government Performance and Results Act (GPRA) analysis or technology assessment The LFMM will strive to strike a balance between complexity and simplicity.

A key component of the domestic liquid fuels market is its interface with the international liquids market. International production, demand, and prices influence the U.S. market, particularly the marginal economics of the U.S. production and cost, which determine final U.S. product prices. The current PMM uses a simple approach of refinery yield vectors and crude oil supply curves that are developed using models employed in production of the International Energy Outlook. At the very least, the LFMM will be as sophisticated as the current PMM with respect to the international liquids market. A new approach towards international liquids markets is under review elsewhere in NEMS (separate from LFMM development); the LFMM will be designed to incorporate such developments.

The LFMM must overcome the shortcomings of the PMM projection capabilities and provide greater confidence in the results. Specifically, the LFMM needs to provide greater simplicity within the technology and conversion representations, while at the same time preserving sufficient integrity in the refinery and market representation to adequately project product prices and minimize over-optimization tendencies. The LFMM must also include sufficient flexibility to adapt to complex emerging policy and market environments, and to reflect the consequences of biofuels and alternative fuels penetration, as well as a contracting refining infrastructure. The LFMM should be as simple as possible without compromising its purpose and operation within the overall NEMS platform.

Additional improvements of the LFMM over the existing PMM will include the following:

- The LFMM will contain somewhat greater regional detail, including a break-out of California in PADD V, due to that State's particular fuel specifications and requirements as well as policies (such as the Low Carbon Fuel Standard).
- The LFMM will be modeled in a user-friendly modeling platform; the General Algebraic Modeling System (GAMS) high-level modeling system will be the initial choice for developing the LFMM prototype.
- Capacity planning/foresight will be streamlined and updated in the LFMM.
- The LFMM will be constructed to be more amenable to modeling changes that incorporate policy studies.
- The international component will be updated to reflect, at the very least, the interaction between the demand for heavy versus light crudes in the U.S. and the light/heavy oil price differential.
- The alternative fuels representation will be updated to a more defensible competitive technology algorithm.

LFMM Capabilities for Special Policy Studies

Special policy studies may involve issues that will specifically impact technology, operations, fuel quality, or other aspects of refining. The LFMM refining representations and their interface with NEMS must include adequate technical and economic detail to address these issues, again without adding undo complexity to NEMS. In other cases, studies may involve detailed refining analyses that do not warrant the full energy projection capabilities of NEMS. The LFMM should have the capability to operate as a single standalone aggregate refinery modeling system. In that sense, the underlying information support structure for both potential applications should be identical, but the analytical purpose should dictate the aggregations made to support the particular type of analysis.

Software Considerations

The LFMM should be developed according to modern software design principles. The underlying LP should be structured and coded in such a way as to be readily understood and modified by an experienced Operations Research Analyst. In keeping with good modeling practice, the LP model and data should be separated. Furthermore, the modeling platform of the LP should be easily integrated within the NEMS framework and the model data and structure should be flexibly designed to easily address new types of liquid fuel policies, laws, and regulations. Finally, the LFMM must run in a timely manner relative to other NEMS modules since it will be executed approximately 200 times in a NEMS cycle.[2]

[2] Within any given NEMS model year, each NEMS module is typically executed 6-8 times as the model iterates between the supply and demand modules as it looks for a demand-price equilibrium. The current NEMS projection horizon is from 2008-2035; 28 years multiplied by eight iterations per year yields 224 potential executions of the LFMM for one NEMS cycle.

3. Background

Current PMM Approach

The current model platform of the PMM consists of a regional refinery LP formulation for five geographic regions (defined per the U.S. PADD regions). Capacities of individual refineries are aggregated into a complex and a marginal (simple configuration) refinery for each region. The two refining types are meant to represent the range of complexity of operations and to mitigate the over-optimization associated with aggregation of all capacity and capacity types into a single refinery. The PMM uses simple adders to model the cost of distributing refined products to demand regions.

Refined product demands are input from the Residential, Commercial, Industrial, Transportation, and Electricity Market modules with end-use demand specified at the Census Division level. A transportation structure links the aggregate PADD-level production with Census Region demand.

The PMM categorizes domestic and imported crude into five aggregate crude quality types. The different crudes types are processed in the crude distillation units, which yield a set of crude-specific intermediate streams. The quality of the intermediates produced is represented as a linear combination of "high" and "low" value properties. For example, a crude category that yields a heavy gas oil intermediate with a sulfur content of 1.0 percent by weight may be represented as a 50:50 mix of 0.3 percent by weight low sulfur heavy gas oil intermediate and 1.7 percent by weight high sulfur heavy gas oil intermediate. More than one quality parameter is represented for each intermediate, so an intermediate stream from crude distillation will include more than a single 'high" and "low" set. In the heavy gas oil case, intermediates are also categorized by chemical makeup, i.e., "paraffinic" or "naphthenic." Therefore, crude distillation can yield paraffinic low sulfur heavy gas oil, paraffinic high sulfur heavy gas oil, naphthenic low sulfur heavy gas oil, and naphthenic high sulfur heavy gas oil.

Intermediate streams from crude distillation are further processed in other downstream refinery process technologies and/or are blended to final product. Downstream from the crude distillation process, the technology representations include a yield vector for each intermediate quality category. The output once again consists of sets of additional quality-categorized intermediates. Eventually all downstream intermediate streams are blended to yield final products.

The PMM allows for capacity expansion by processing unit. Expansions proceed when the value received from the individual product sales exceeds the investment and operating costs of the new unit. Annual capital charges for investments are expressed on a per-barrel of daily throughput basis and incorporated into the process costs along with variable operating costs. Capacity expansions are done in three-year increments. The PMM looks ahead three years and determines the optimal capacities needed to meet expected demand three years out. The PMM limits the amount of capacity that can be built in the first year. Any remaining required capacity is built in the next two years. The annual apportionment of total new capacity is done on a percentage basis, and is an exogenous input. The current PMM does not provide for shutdowns or capacity retirements.

In some cases, the PMM refinery technology options include a high level of detail that adds little or no value to the simulation or the price projection goals of the module. For example, multiple technologies are represented for similar processing alternatives with little relevant difference in inputs, outputs, or economics. There are also some petrochemical options and emission control operations that have little impact on the simulation or price solution.

The PMM reflects the renewable fuel requirements of the Energy Independence and Security Act of 2007 (EISA2007), including the various categories of cellulosic biofuels and biomass diesel. In doing so, the PMM accounts for the production of corn and other grains, as well as the production of cellulosic ethanol, corn ethanol and biodiesel. Legislative requirements and biofuels production technologies are modeled in PMM. The PMM also includes GTL and CTL representations for production of liquid fuels from natural gas and coal.

The PMM also represents natural gas processing activities. The activities include wet gas-dry gas relationships and the processing of the natural gas stream (NGLs).

The international component of supply and demand is represented by four non-U.S. regions that produce liquid product for regional demand and the U.S. import market. Additional links between the U.S. and international markets allow for crude and product imports and exports. The combination of U.S. refining output and net refined product imports provide a set of refined product quantities and prices delivered to Census Regions.

Past Modeling Approaches and Efforts

EIA has considered a variety of approaches to model liquid fuels markets. A common theme among all the approaches is a continuing effort to manage tradeoffs between (1) the quality of the projection that derives from the liquid fuels market representation (this quality is often perceived to be related to model detail), (2) NEMS run time, and (3) modeler time spent collecting data, analyzing results, correcting errors, and updating the model.

Pure Statistical/Econometric Approaches

In a pure statistical/econometric approach, the relationship between product prices and raw material prices (e.g., gasoline prices vis-à-vis crude oil prices) is a “black box” based solely on historical data rather than an understanding of the underlying transformation technologies. This approach can be useful for short-range and non-dynamic projections, but is not useful in the context of NEMS. EIA has experienced the severe limitations of such an approach, including (1) inability to model changes in product specifications such as those required by the Clean Air Act Amendments (CAAA), (2) inability to easily model capacity expansion/revision, and (3) inability to model the competition between the oxygenates ethyl tertiary butyl ether (ETBE) and methyl tertiary butyl ether (MTBE).[3]

Statistical Approximations of Large Refinery LPs

In this approach, a "global" response surface is defined, based on the inputs and outputs of many runs of an underlying complex, time-consuming LP model. The response surface would then (supposedly) serve as a fast, accurate statistical approximation of an LP that would otherwise take too long to run within NEMS. EIA experience has shown this approach to be time-consuming and inappropriate for modeling refinery operations, except in very limited cases.

EIA tried such an approach with the Oil Market Module (OMM) of the Intermediate Future Forecasting System (IFFS), which was the predecessor to NEMS. The OMM used econometric equations to represent the relationship between refinery production costs (i.e., product costs) and product yields. Specifically, the econometric equations used within the OMM "approximate[d] the petroleum product pricing characteristics of the Oil Trade Model (OTM) ... a large linear programming-based representation of domestic and international petroleum product production and consumption."[4] Pseudo-data were generated by running OTM for hundreds of scenarios in which the yield of a reduced set of petroleum products was recorded in response to independently varying product prices over a predefined range. The pseudo-data were used to develop econometric equations. This approach provided only limited value in the OMM because it was impossible to develop a sufficiently accurate response surface of the OTM LP for a broad range of model inputs using available analyst time and resources. Compounding this, the complete set of OTM runs would have needed to be re-done to accurately account for changes in environmental regulations, fuel specifications, etc.

Use of Large LPs and Reduced-Form Modeling to Estimate Parameters of a Smaller Liquids Model LP That Approximates the Behavior of the Detailed LP

In this approach, the LFMM would be based on a larger LP that runs outside of NEMS. For example, if there were a commercially-available model that encompassed all the existing refineries in the U.S., such a model could possibly be used to calibrate an LFMM model in which the U.S. refinery sector was aggregated into a smaller number of technologies and regions. The issue of annual maintenance costs could be significant if this approach were used, because the new laws/policies/specifications would first have to be implemented and tested in the large model and then eventually transferred to the smaller LP model version from information derived from the large model.

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[3]Energy Information Administration, *A Critique of the Oil Market Module*, memo by Stacy MacIntyre, Oil and Gas Analysis Branch within the Energy Supply and Conversion Division of the Office of Integrated Analysis and Forecasting, EIA/DOE (Washington, DC, January 1992).

[4]Decision Analysis Corporation, *Model Documentation Report: The Oil Market Module*, for the Petroleum Marketing Division within EIA/DOE, Contract No. DE-AC01-87E119801 (September 1990).

For a few years, EIA used a five-region refinery model (a version of the PMM currently in use) that ran outside of NEMS in order to develop a three-region refinery model for use within NEMS. The five-region model was considered to be too slow to run within NEMS, but the three-region version was fast enough. Over time, the difficulties arising from aggregating five regions to three regions outweighed the benefits in solution time. Currently, the domestic liquid fuels markets portion of NEMS (the PMM) is a five-region model.

Linear Optimization Representation of Refineries

The current liquid fuels module in NEMS, the PMM, is a linear programming representation of U.S. petroleum refineries. The PMM was developed in-house and was not based on other existing LP formulations of the U.S. refinery market. It was designed from the beginning to be integrated within NEMS and to provide a consistent set of refinery market outputs, including:

- Equilibrium crude and product import quantities and prices
- Domestic product prices
- Refinery margins

subject to satisfaction of domestic liquids demand

The PMM was also designed to address policies that added financial incentives or taxes to delivered products or input fuels. However, the PMM was not designed to address some of the more recent renewable fuel policies, and it suffers from a number of modeling issues including: (1) the number of intermediate streams is too large and unnecessary for use within NEMS, (2) its model structure is not easily tailored to new laws and regulations and the integration of alternative liquid fuels within the U.S. liquids market, and (3) alternate fuels are not well integrated within the U.S. liquids market.

Nonlinear Optimization Representations of Refineries

Refineries use complex nonlinear models to characterize daily refinery operations and accurately represent the product streams, cut-points, prices and margins. Such models have not been used within NEMS or the NEMS predecessors because (1) commercial packages were too expensive and too slow to integrate within NEMS and (2) EIA did not have the human resources (including experienced refinery engineers/operators) to run such models.

4. Input and Output Requirements

General Requirements for NEMS

Within the NEMS framework, the LFMM will produce regionally disaggregated annual projections of:

- Delivered cost, insurance, and freight (CIF) prices of (1) liquid fuels produced, (2) other petroleum products
- Prices of (1) domestic inputs to refineries (including crude oil), and (2) imported crude oil, imported liquid fuels, and other imported refinery inputs. These input prices are developed in conjunction with other modules of NEMS, such as the Oil and Gas Supply Module
- Levels of domestic regional refinery operations (processing and blending) and transport operations
- Levels of domestic regional alternative fuels production and transport operations
- Volumes of domestic and imported crude oils processed by U.S. refineries
- Refinery energy consumption, by fuel, and CO_2 emissions
- Refining capacity utilization, additions, and retirements (shut-downs)
- Alternative fuels capacity utilization, additions, and retirements (shut-downs)
- Transport capacity utilization.

The projected end-use prices of refined petroleum products (some of which may include bio-fuels and other alternative fuels) in each end-use demand region are defined as the sum of:

- The marginal cost of refinery production computed by the model and reflecting allocations to the various refined products of:
    - Average delivered price of crude oil (based on the projected world oil price)
    - Cost of other refinery inputs or blendstocks
    - Cost of refinery energy use
    - Other variable refining costs (catalysts and chemicals, etc.)
    - Fixed costs
    - Capital charges and return on refinery investment
- Transportation cost from refinery to terminal, also computed by the model
- Distribution costs and mark-ups from terminal to end-use point
- Federal and State taxes
- Other mark-ups relating to the cost of complying with policy mandates such as Renewable Fuels Standard 2

The first item is the computed shadow price of the given product in the given region. The second item is an exogenously specified cost for the given product/refining region/end-use region/mode combination; this cost contributes to the LFMM objective function. The third and fourth items are exogenously specified costs for the given product/end-use region combination; these costs also appear in the LFMM objective function.

The LFMM must be fully integrated with the rest of NEMS. In particular, it must:

- Support the NEMS solution algorithm for computing year-by-year energy/economy equilibrium
- Accept specified inputs from NEMS
- Return specified values (primarily CIF prices of petroleum products supplied to each end-use market).

Input and Output Boundaries of the LFMM

The relationship of the LFMM to other NEMS modules will be defined by the information flows between the LFMM and these modules, managed by the NEMS Integrating Module.

Within the NEMS recursive solution procedure, the LFMM will return solutions that meet a set of fixed regional and total demands for liquid fuels and other petroleum products at minimum total cost (refining cost + alternative fuels production cost + supply cost). The fixed product demands will be conveyed to the LFMM by the NEMS Integrating Module. (Here, the term "fixed" means fixed for a given year and NEMS iteration for that year.)

Figure 4.1: LFMM - NEMS Information Flows

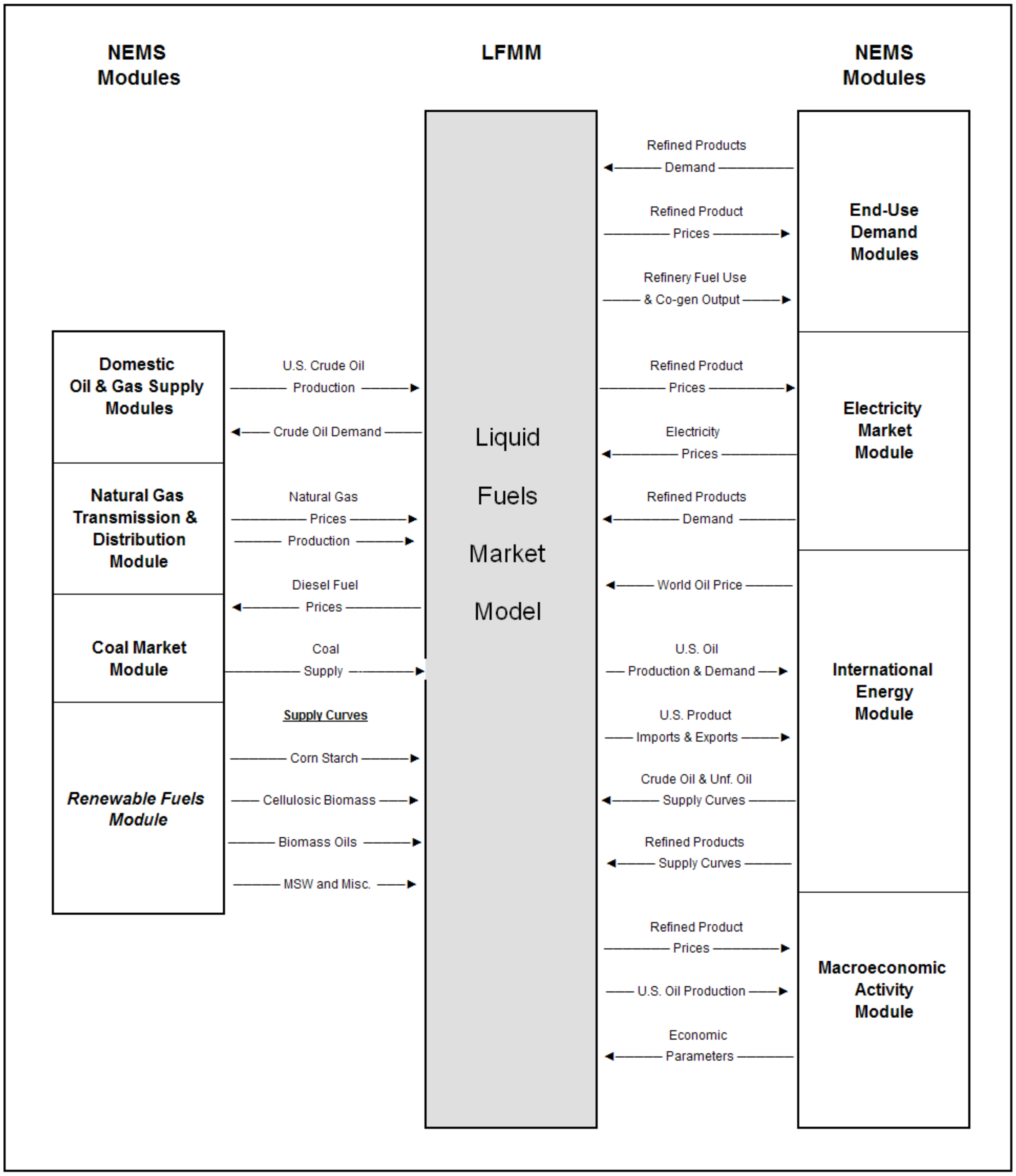
LFMM Outputs		LFMM Inputs			
		from NEMS		Exogenous	
Liquid fuels prices	✓	Petroleum product demand	✓	Process unit characterizations	✓
Crude oil consumption	✓	U.S. crude oil production	✓	Process unit capacities (initial)	✓
Crude oil imports	✓	World oil price	✓	Process unit capital costs	✓
Petroleum product imports	✓	Imported crude oil supply curves	✓	Product specifications	✓
Petroleum product exports	✓	Imported unf. oil supply curves	✓	Refining costs	✓
Refining process activity	✓	Imported product supply curves	✓	Transport and distribution costs	✓
Refinery processing gain	✓	Natural gas production	✓	Federal and state taxes	✓
Refinery fuel use and CO2 generation	✓	Natural gas prices	✓	Refinery CHP characterizations	✓
Refinery combined heat and power (CHP)	✓	Electricity prices	✓	Refinery CHP capacities (initial)	✓
Refining capacity additions	✓	Biomass supply curves	✓	CO2 prices (emissions policy)	✓
Refining capital expenditures	✓	Coal supply curves	✓	Economic parameters	✓
		Macroeconomic variables	✓	Agricultural feed supply curves	✓
Ethanol consumption (in E10 and E85)	✓				
Ethanol price (rack, ex VEETC)	✓				
NGL production	✓				
CTL, GTL production	✓				
Biofuels (inc. BTL) production	✓				

The prices computed by the LFMM will be returned to the NEMS end-use demand modules through the NEMS Integrating Module and will be used to re-estimate end-use demands in the NEMS iterative solution procedure.

Figure 4.1 and **Figure 4.2** summarize and illustrate the information flow linkages between the LFMM and NEMS. The figures indicate that the LFMM will preserve essentially all the existing PMM-NEMS information flows, and in addition, will accept inputs, in the form of supply functions, from the Renewable Fuels Module of NEMS.

Additional detail regarding the inputs and outputs required of the LFMM can be found in Section Chapter 0 of the Appendix.

Figure 4.2: Linkages Between LFMM and NEMS



LFMM Reporting Requirements

Currently, the primary NEMS output, "FTAB," has 12 tables dedicated to the output of the Liquid Fuels Model. These tables are:

- Liquid Fuels Supply and Disposition

- Petroleum Product Prices
- International Liquids Supply and Disposition Summary
- Refinery Industry Energy Consumption
- Domestic Refinery Distillation Base Capacity, Expansion, and Utilization
- Domestic Refinery Production by Region
- Components of Selected Petroleum Product Prices
- Refinery Process Unit Capacity
- Alternative Fuels Table
- Equilibrium Import Petroleum Supply
- Equilibrium Import Petroleum Product Supply
- Petroleum Balances

The information in these output tables is the core requirement for the proposed LFMM. These tables will be modified as needed to reflect the new model topology. In addition, the LFMM product prices, fuel consumption, and feedstock requirements are included in output tables dedicated to other demand modules, supply modules, and conversion modules. The LFMM LP structure and output will be saved for debugging purposes. The LFMM will also create summary reports as necessary.

LFMM Data Sources

Categories of Refinery Modeling Data

Data needed to populate the LFMM fall into seven broad categories:

1. Refining process data (input/output coefficients for the various refining processes)
2. Process investment data
3. Maximum process capacity utilization rates
4. Crude oil assays
5. Blend stock properties for specification blending of refined products
6. Allowable assignments of blendstocks to finished products
7. Boundary conditions that model solutions must satisfy (e.g., existing refining capital stock, refined product specifications, policy and regulatory constraints, etc.)

This section addresses only the first five of these categories. Category 6 reflects refining industry practice and is based on experience. Category 7 is based on information readily available in public documents.

Figure 4.3 lists the refining processes to be represented in the LFMM and, for each process, the parameters that determine the set of operating modes to be represented. **Figure 4.4** indicates the input and output (I/O) coefficients that define the operating modes for the various processes.

Each refining process (e.g., FCC, coking, etc.) shown in **Figure 4.3** will be described by a corresponding table of process data. Each *column* in a process table denotes a particular operating mode – that is, a unique combination of operating parameters: feed stream type(s) or feed stream properties, operating conditions (severity, conversion, etc.), and other parameters.

Each *row* in a process table denotes a particular input to or output of the process. Each operating mode (column) in a process table will generate a corresponding variable in the LFMM.

Figure 4.5 lists the economic parameters needed to compute the investment costs and capital charges associated with additions to process capacity. Most of these parameters are process-specific; some are region specific. (Most of the indicated parameters do not go into the refinery model proper; rather they are used to compute the investment and capital charge coefficients that do go into the model. In **Figure 4.5:**

- ISBL is the onsite investment (or Inside Battery Limits.) The ISBL field costs typically include the direct cost such as major equipment, bulk materials, direct labor costs for installation, construction subcontracts, and other indirect costs.
- OSBL is the offsite investment (or Outside Battery Limits.) The OSBL costs typically include the cost of cooling water, steam and electric power generation and distribution, fuel oil and fuel gas facilities, water supply, etc.
- USGC stands for United States Gulf Coast.

Figure 4.3: Refinery Processes and Operating Mode Parameters

Refinery Processes	Operating Mode Parameters
Crude Oil Distillation	Crude oil
Atmospheric crude unit	
Vacuum crude unit	
Residual Oil Upgrading	Feed quality type
Coking, delayed	Crude oil type (for vacuum resid feeds)
Coking, fluid bed	Other feed type
Resid hydrocracking	(e.g., FCC Hvy cycle stock)
Solvent deasphalting	Solvent (for SDA only)
Catalytic Cracking (FCC)	Feed quality type
	Boiling range (HVGO, LVGO, SRD, Resid)
	Sulfur and "hetero-" content
	Pretreat status (Hydrotreated or not)
	Conversion level
Hydrocracking	Feed quality type
Hydrocracking: distillate	Crude oil type (for straight run feeds)
Hydrocracking: gas oil	Other feed type (e.g., FCC Hyc cycle stock)
Hydrocracking: resid	Operation (max gasoline or max jet)
Upgrading	
Alkylation	Feed type (Carbon number, etc.)
Dimer/Poly	Feed type (Carbon number, etc.)
C4 Isomerization	Feed type (Source)
C5/C6 Isomerization	Feed quality type (Crude oil type)
Catalytic Reforming	Feed quality type
Low Pressure	Boiling range
High Pressure	Crude oil type (for N and A content)
	Bnz precursor status (Removed or not)
	Severity (RON)
Hydrotreating	Feed quality type
FCC feed hydrofining	Crude oil type (for straight run feeds)
FCC naphtha hydrotreating	Other feed type (e.g., coker naphtha, FCC
Reformer feed hydrotreating	naphtha, FCC light cycle oil)
Benzene saturation	Sulfur content
Jet fuel hydrotreating	Severity (target sulfur content)
Distillate hydrotreating	
Distillate dearomatization	
Resid hydrotreating	
Green diesel production	
Splitting/Fractionation	Feed quality type
Reformer feed splitter	Desired separation
FCC naphtha splitter	(e.g., C_4/C_5+, T_{90} control)
Debutanizer	
Depentanizer	
Non-fuel-producing Operations	Feed quality type
Aromatics extraction	
Lube and wax production	
Asphalt production	
Sulfur recovery/production	
Refinery Utilities	
Hydrogen production	Feed type (Natural gas, refinery streams)
Hydrogen recovery	Spent hydrogen type (source process)
FCC regenerator	
Refinery fuel	Fuel type (Natural gas, refinery streams)
Steam generation	
CHP generation	

Note:
Each process is represented by a set of operating mode variables, each of which denotes a particular combination of parameters (e.g., a particular combination of a feed quality type (say. lgt. naphtha X) and a severity (say, 100 RON)).

Figure 4.4: Process I/O Coefficients for Operating Mode Variables

Data Type	Data Element	Units of Measure
Utility Consumption	Fuel	FOEB / Bbl
	Power	Kwh / Bbl
	Steam	Klb / Bbl
Capacity Consumption	Cap. Con	Bbl cap / Bbl thru
Streams	Inputs	Bbl / Bbl
	Outputs	Bbl / Bbl

Note:
For any given process, the input and output coefficients for each operating mode correspond to specific refinery intermediate streams that are, respectively, inputs to and outputs of that process when operating in that mode.

Figure 4.5: Parameters for Computing Refining Process Investment Costs

Investment Cost (K $/Bbl/day)

*	**Standard Onsite (ISBL) Investments for New Process Capacity (K $/Bbl/day)**
	(Grassroots units, USGC location, ISBL only, base unit size, 2008)
	Multipliers to Standard ISBL Investment Estimates ***Required***
*	Offsite (OSBL) factor
	Location factor (by PADD)
	Construction cost inflation factor (by year)
*	Technology risk factor (for new processes)
*	**Multipliers to Standard ISBL Investments, for non-Grassroots Investment**
	Expansion investment
	Retro-fit investment
	Capacity creep investment
*	**Exponential Investment Function Parameters**
	Base unit size (standard ISBL investment)
	Capital cost for base unit size (standard ISBL investment
	Exponent

Capital Charge ($/Bbl)

	Measure of Required Rate of Return on Investment
	Hurdle rate OR Internal rate of return OR Cost of capital OR years to pay-back
	Accounting Parameters
	Depreciation schedule (e.g., double declining balance, etc.)
*	Construction period (years)
	Tax rates: federal
	Tax rates: local
	Investment tax credits (if any)
	Fixed charges

Capacity Utilization (%)

*	**On-stream Rate (Service Factor)**
	Maximum rate of utilization of nameplate capacity (K Bbl/day)

Note:
The items denoted by an asterisk (*) are process-specific. The other items are applicable to all processes uniformly.

Prospective Sources of Refining Data

Prospective sources of the necessary refining data are listed below.

1. EIA Refinery Survey Data (SISQuery)

2. Existing refinery models
   a. PMM
   b. GRTMPS
   c. MathPro's ARMS model
   d. PetroPlan (would have to be purchased)

3. Existing crude assay libraries (would have to be purchased)

4. EPA's data on average properties of produced gasoline, as dis-aggregated as possible

5. Textbooks
   a. *Petroleum Refining* (4^{th} or 5^{th} Edition), Gary and Handwerke
   b. *Petroleum Refinery Process Economics* (2nd Edition), Maples
   c. *Refining Processes Handbook*, Parkash
   d. *Handbook of Petroleum Refining Processes* (1st and 2nd Editions), Meyers
   e. *Catalytic Reforming*, Little

6. Trade Publications (and their web sites)
   a. *Oil & Gas Journal*
   b. *Hydrocarbon Processing*
   c. *Petroleum Technology Quarterly*

7. Technical papers presented at National Petrochemical & Refiners Association (NPRA) meetings

8. Technology Providers (under confidentiality agreements)
   a. UOP (cat cracking, reforming, hydrotreating, alkylation, etc.)
   b. CD Tech (FCC naphtha hydrotreating, alkylation)
   c. Axens (FCC naphtha hydrotreating, distillate hydrotreating, etc.)
   d. KBR (heavy oil processing)
   e. ExxonMobil (cat cracking, reforming, hydrotreating, etc.)

In addition to the above sources, the refining companies may well be willing to contribute to the LFMM effort by reviewing and commenting on the refining data once it has been collected, processed, and organized; however, they are not likely to be primary sources.

It has been recommended [3] that designing and building the process tables should be the first order of business. Unfortunately, building out the process tables is not an orderly, linear process;

it's more like putting together a jigsaw puzzle or doing detective work. For example, one is unlikely to find all the input/output data for any given process in a single primary data source (textbooks, journals, etc.). Rather, the description of each process has to be assembled out of fragmentary information from multiple sources. The same is generally true for blend stock properties and investment estimates.

Consequently, given the schedule for developing the LFMM prototype, the most practical course of action is probably to mine the EIA models for refining data to the maximum extent possible before moving on to the other sources. However, even that approach will be neither simple nor straightforward.

5. Classification Plan

Definitions

This section of the CDR defines a number of terms that are used throughout the document. The intention of presenting all these definitions in one place is to facilitate the discussion of LFMM requirements and design.

Attributes and Domains

- An attribute is a named property, or "dimension," of a model, and is expressed in both the model and the data underlying the model.
- A domain is a named set of terms defined under one or more attributes. In general, each term in a domain denotes a particular item represented in the model.

A domain may serve more than one attribute, but each attribute has only one domain (as shown in the last two examples in the figure below).

As **Figure 5.1** suggests, attributes and domains are comparable to, respectively, the "indices" and "index sets" that commonly appear in discussions of complex LP models.

Attribute and domain are terms usually used to denote elements of relational databases. However, these terms and the relational database concepts to which they refer are also relevant to optimization models. Use of this terminology here is not simply a matter of style or preference. Rather, it denotes the use of a common data architecture spanning the model and its underlying data. This approach facilitates the use of relational database capabilities for managing modeling data. It also provides a logical framework unifying model and data, and simplifies the computational requirements for creating and managing the model.

Figure 5.1: Some Examples of Attributes and Their Domains

Identifier	Attribute	Domain
Ref	Refining region	{PADD 1, PADD 2, PADD 3, PADD 4, PADD 5}
Dem	Demand region	{CD 1, CD 2, CD 3, CD 4, ... CD 9}
Pro	Refining Process	{ACU, VCU, FCC, Coking, Hydrcrk, Alky, Isom, …}
Str	Intermediate Stream	{Lt. St. Run, Hvy. St. Run,. . ., Desulf VGO, Lt. Cyc. Oil, . . .}
Dcr	Domestic Crude	{Lt. Swt., Lt. Sour, Med Swt., Med Sour, Hvy. Sour}
Icr	Imported Crude	{Lt. Swt., Lt. Sour, Med Swt., Med Sour, Hvy. Sour}

Model Statement and Model Instance

A *model statement* is a complete symbolic representation of a model's mathematical structure and content; it is a mathematical construct independent of any specific items or numerical data that one may associate with the model. The LFMM *model design* presented in this document is a model statement. (The analytical process of developing a complete model statement that can be reduced to practice is called *model formulation*.)

A *model instance* is a complete, quantified expression of a model statement that can be processed and solved. A solver-ready model instance comprises explicit equations, variables, and numerical coefficients. Physically, a model instance exists as a computer-readable file – often referred to as a matrix file – with content and format such that it can be processed by the solver of choice. (The computational process of producing a model instance from a model statement and a particular set of input elements is frequently called *matrix generation*.)

Matrix Schematic (Block Diagram) Representation of LP Models

An LP model statement can be expressed at the conceptual level in terms of (1) a set of generalized algebraic relationships between variables, defined over various index sets, or (2) a schematic diagram of the model's detached coefficient matrix, also defined over index sets or domains. The second approach, called a *matrix schematic*, offers a number of advantages in visualizing and documenting complex LP models, such as refining models, and it is the approach followed here.

- A *detached coefficient matrix* is a two-dimensional array of numerical values. Each column denotes a variable, each row denotes a constraint (equation or inequality), and each number is a coefficient on a variable. An LP model's detached coefficient matrix is usually quite large and extremely sparse; such properties dictate the use of symbolic, rather than explicit, schemes for expressing matrices. One such scheme is the *block diagram*, an example of which is shown below in **Figure 5.2**.[5]

[5]This block diagram represents the PMM. It is drawn from Appendix B of [14].

Figure 5.2: PMM Linear Program Structure in Block Diagram Form

Table B1. PMM Linear Program Structure

PMM Linear Program Overview

	Crude Trans.	Purchases Crude Oil, Other Inputs	Crude Distillation	Other Process Unit Operations	Capacity Expansion	Ethanol	Blending	Product Sales	Product Trans.	Row Type	RHS
Objective	-ct	-c	-o	-o	-i	-i -fd/+co		+p	-pt	NC	Max
Crude Oil Balance	+1 +1 -1	+1 +1 +1	-1 -1							GE	0
Intermediate Stream Balance			+y +y	-1 -1 +y +y		-1 +1 -1 +1	-1 -1			GE	0
Utilities		+1	-u	-u +1		-u				GE	0
Policy Constraints				+z -z				+z -z		GE LE	0
Environmental Constraints			+q	+q						GE LE	E
Unit Capacities			+1	+1	-1	+1				LE	K
Quality Specifications							+q +q -Q			GE LE	0
Product Sales							-1	-1	-1 +1 +1 -1	GE	0
Pipeline/Marine Capacities	+1 +1					-1			+1 +1	LE	C
Bounds	Up/Lo/Fix	Up/Lo/Fix				Up		Up/Lo/Fix			

Legend: c = crude cost; p = price; Q = product specifications; y = yield; z = policy ratio; C = pipeline/marine capacity; u = utility consumption; q = stream quality; E = environmental quality limit; K = unit capacity; ct = crude transportation cost; i = investment cost; o = operating cost; pt = product transportation cost; fd/co=Feedstock /Co-product credit

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- A *block diagram* is a symbolic matrix representation of a detached coefficient matrix. As the column and row names in the diagram suggest:
    - Each column denotes a collection of logically similar variables, representing similar physical activities, and having similar physical representations in the explicit model.
    - Each row denotes a collection of logically similar constraints, representing similar relationships between variables, and having similar physical representations in the model.

Though not shown in the diagram, the columns and rows are defined over index sets.

Some of the row/column intersections in a block diagram contain symbols, called blocks. Each block denotes an array of matrix coefficients (some of which may be simply +1's or -1's) defined over the same attributes and domains as the intersecting column and row.

- The terms *column strip*, *row strip*, and *block* are frequently used to denote respectively, a column in a block diagram, a row in a block diagram, and an array of matrix coefficients.

The block diagram is a useful device for delineating an LP model's overall architecture and scope. It is not a complete model statement, however, and it does not contain sufficient information to support model implementation. For that purpose – and hence for the purposes of this CDR – one must expand the block diagram framework.

- A *matrix schematic* is a representation of a model's detached coefficient matrix in sufficient detail to support implementation. A matrix schematic comprises four elements:
    - A *block diagram*, as described above
    - A *column strip catalog* – a complete listing of the model's column strips, together with the attributes over which each strip is defined and brief description of each strip
    - A *row strip catalog* – a complete listing of the model's row strips, together with the attributes over which each strip is defined and brief description of each strip
    - A *block catalog* – a complete listing of the named blocks in the model statement (excluding the +1 and -1 arrays), together with pointers to the database tables or other elements that contain the actual numerical values that go into each of the various blocks

  The three catalogs are essential drivers for all matrix generation procedures.

Case Management

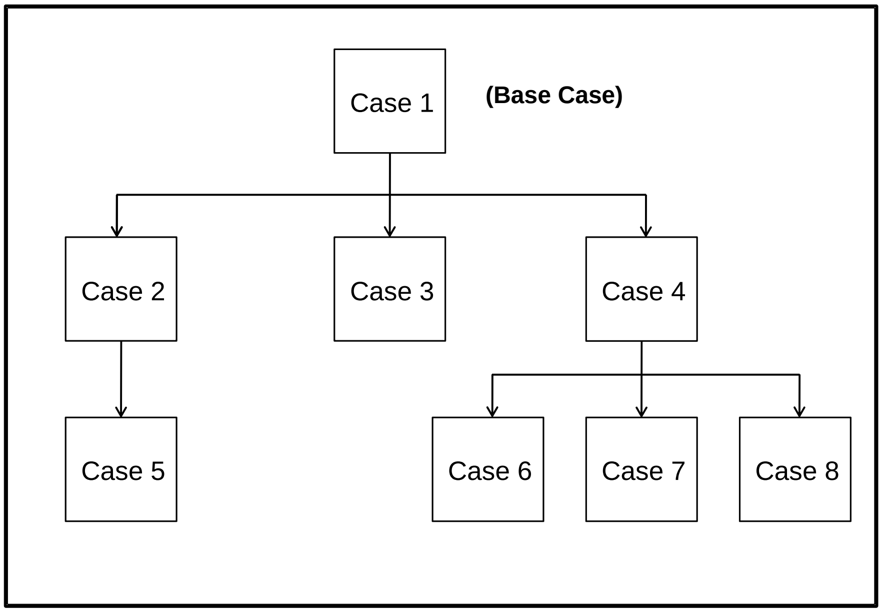
- A *case* is a complete computer-readable expression of one model instance.[6] A case may comprise some or all the following objects:
    - Data arrays – relations or tables
        - Primary data
        - Matrix coefficients
        - Solution values
        - Control parameters
    - Domains
    - The model statement
    - A model instance (in solver input format)
    - An advanced starting solution for the model instance (in solver input format)

[6] The ACT file, used in the PMM, is generally similar to this definition of case.

- Control parameters

- A *case tree* is a collection of multiple cases, arranged in a hierarchical or tree structured array, as illustrated below in **Figure 5.3**.

Figure 5.3: A Hierarchical Case Tree



- Each case in a case tree is a descendant (or *child*) of an existing (*parent*) case in the model's database. A child case is created by adding, deleting, or modifying at least one element in an existing (parent) case. Each case in the case tree has a unique-user specified name. Changes made in any case are automatically inherited by all descendant cases. Deleting a case causes deletion of all descendant cases.

- Each case in a case tree is registered in a *case catalog*, which shows the case name, parent case, time of most recent update, and the status of the case's model instance (generated, solved, infeasible, etc.). The user creates and deletes cases through the case tree catalog.

All cases in a hierarchical case tree are virtual. That is, for each child case, the modeling platform physically stores only those objects that are different from their counterparts in the parent case. However, the user sees and has access to the entire case (including all inherited elements) as if it were physically stored in its entirety.

LFMM Attributes

Figure 5.4 lists and defines the attributes of the LFMM model and indicates that some attributes are defined as sub-attributes of other ones. A sub-attribute is a pure sub-set of another attribute (and the same relationship holds for the corresponding domains).

The attributes shown in **Figure 5.4** not only delineate the overall structure of the Classification Plan but also are integral elements of the model itself (as described in Chapter 6). Some of the attributes shown in the figure (e.g., RET_FIT, SOS2, etc.) may not immediately appear necessary or relevant. However, the role of these attributes in the model should become clear in Chapter 6.

Figure 5.4: LFMM Attributes

Attribute	Identifier	Definition
Region	REGION	Supply or demand region
Refining region	REF_REG	Refining regions, sub-attribute of REGION
Alternative fuel region	ALT_REG	Alternative fuels production region, sub-attribute of REGION
Demand region	DEM_REG	End-use demand regions (census regions), sub-attribute of REGION
Source	SOURCE	Source of refinery inputs: domestic or foreign supply source (geographic)
Crude oil - domestic	CRUDE_D	Domestic crude types; sub-attribute of CRUDE
Crude oil - imported	CRUDE_I	Imported crude types; sub-attribute of CRUDE
Crude oil	CRUDE	All crude oil types
Refinery input	REF_INP	Refinery input streams
Unfinished oil - purchased	UNF_OIL	Sub-attribute of REF_INP: vacuum gas oil, vacuum resid, etc.
Blendstock - purchased	BLN_STK	Sub-attribute of REF_INP: butanes, NGL, alkylate, iso-octane, etc.
Alternative fuels production process	ALT_UNIT	Process for producing renewable or alternative fuel
Alternative fuels feedstocks	ALT_FEED	Hydrocarbon feedstocks for alternative fuels production (coal, nat gas)
Alternative fuel - purchased	ALT_FUEL	Sub-attribute of REF_INP: CTL, GTL, green diesel, etc.
Ethanol type	ETH_TYPE	Corn, cellulosic, imported, sub-attribute of RFS_CAT
Biomass feeds	RFS_FEED	Biomass feedstocks for renewable fuels production
RFS2 fuels type	RFS_CAT	RFS2 fuel categories, sub-set of SPC_CON
RFS2 fuel pathway	RFS_PATH	RFS2 production pathways (feed --> process --> product)
Finished product - refinery-produced	PROD_R	Sub-attribute of PROD
Finished product - imported	PROD_I	Sub-attribute of PROD
Finished product - terminal blended	PROD_T	Sub-attribute of PROD, includes E85
Finished product	PROD	All refined products and alternative fuels products, regardless of source
Refinery energy form	NRG_REF	Steam, fuel, electricity
Refinery energy purchase	NRG_PUR	Natural gas, electricity
Intermediate refinery stream	I_STREAM	Refinery-produced and purchased streams
Refinery crude running unit	CDU	Atmospheric and vacuum distillation
Refinery process unit	UNIT	Refinery process units
Refinery utility	UTIL	Refinery utilities
Process operating mode	OP_MODE	Operating modes (process and utility)
Capacity retrofit option	RET_FIT	Old service / new service pairing
Gasoline quality/specification	QUAL_G	Specifications and corresponding blendstock properties
E85 quality/specification	QUAL_E	Specifications and corresponding blendstock properties
Distillate fuel quality/specification	QUAL_D	Specifications and corresponding blendstock properties
Resid fuel quality/specification	QUAL_R	Specifications and corresponding blendstock properties
Stream transfer	STR_TRAN	For simulating fractionation or cut point shifts
Gasoline type -base blend	GASB	CBOB, RBOB, CARBOB, etc.
Gasoline type -finished	GASO	CG, RFG, CaRB
Distillate fuel	DIST	Distillate fuels, Including jet fuel
Residual fuel	RESID	Low, med, high sulfur residual oils
Recipe-blended product	REC_PROD	Sub-attribute of PROD
Recipe blending option	REC_BLN	Blending recipe expressed as blendstock volume fractions
Price level	PRICE	Price steps for representing price/volume curves
Special constraint (all)	SPC_CON	Special or ad hoc constraints
Special constraint (transport)	SPC_CONT	Sub-set of SPC_CON for representing transport constraints
Special constraint (refining)	SPC_CONR	Sub-set of SPC_CON for representing refining constraints
Special constraint (environmental)	SPC_CONE	Sub-set of SPC_CON for representing environmental constraints
Transportation mode	TR_MODE	Pipeline, barge, tanker
Transportation route node	TR_SEG	Transport route segment (adjacent pair of nodes on a specified route)
Accounting category (revenue/expense)	ACCNTG	Revenue and cost categories for summarizing refinery economics
CO2 source	CO2_SRC	Source of refinery CO2: natural gas, still gas, catalyst coke, etc.
SOS2 vector	SOS2	For representing piece-wise linear functions
Season	SEASON	Summer, winter

Selected LFMM Domains

The following figures illustrate the most important domains in the Classification Plan that can be defined at the current stage of LFMM development. In most cases, the contents of these figures differ from the corresponding index sets in the PMM.[7]

- **Figure 5.5** shows refining regions and demand regions. There are eight refining regions: seven U.S. regions (one of which is California) and one off-shore region (denoting the short-haul refineries in the Western Atlantic Basin that serve U.S. markets).

- **Figure 5.6** shows crude oil inputs to U.S. refineries: seven types of imported and domestic crude oils, including two types of Canadian oil sands crudes.

- **Figure 5.7** shows non-crude-oil inputs (unfinished oils, hydrocarbon blendstocks, and alternative fuels) to U.S. refineries.

- **Figure 5.8** shows the individual refining processes in the regional refining representations.

- **Figure 5.9** shows the slate of refinery-produced petroleum products (excluding terminal-blended products, such as E10 and E85, which are represented elsewhere).

- **Figure 5.10** shows the sets of blending specifications for specification-blended products produced in refineries, by product category. These sets of specifications also denote the sets of blending properties carried in the model for the refinery streams that are blended into the various product pools.

- **Figure 5.11** shows the sets of feedstocks for the production of alternative fuels: seven biomass feeds (specified in EISA and the RFS2 rule) for production of renewable fuels and three feeds (coal, natural gas, and biomass oils) for production of CTL, GTL, and green diesel, respectively.

- **Figure 5.12** shows the five types or categories of renewable fuels defined in EISA, each of which carries a corresponding type of Renewable Information Number (RIN) for certification of compliance with the mandated renewable fuels volumes of a given year.

- **Figure 5.13** shows the set of EPA-certified pathways for producing renewable fuels (as specified in the RFS2 rule). Each pathway is a unique combination of biomass feedstock, process type, and renewable fuel product. A given pathway may encompass one or more distinct technologies or proprietary process designs.

- **Figure 5.14** shows the transportation modes (for refinery and alternative fuels input and output streams).

[7] The rationales for these differences are discussed in subsequent sections of the report.

Figure 5.5: Refining, Alternative Fuels, and Demand Regions

Attributes		
Main Attrib.	**Sub-Attrib.**	**Regions**
REGION	**REF_REG**	**Refining**
		PADD 1
		PADD 2 Great Lakes
		PADD 2 Central
		PADD 3 Gulf Coast
		PADD 3 Inland
		PADDs 4 & 5 (ex CA)
		California
		E.Canada/Caribbean
	ALT_REG	**Alternative Fuels**
		Census Division 1
		Census Division 2
		Census Division 3
		Census Division 4
		Census Division 5
		Census Division 6
		Census Division 7
		Census Division 8
		Census Division 9
	DEM_REG	**Demand**
		Census Division 1
		Census Division 2
		Census Division 3
		Census Division 4
		Census Division 5
		Census Division 6
		Census Division 7
		Census Division 8
		Census Division 9

Figure 5.6: Refinery Inputs (Crude Oils)

Crude Oil Categories	Specimen Crude	Crude Oil Properties		
		API Gravity	Sulfur (Wt%)	Vac. Resid. Yield (Vol%)
Light sweet	WTI	25-60	<0.5	<15
Light sour	WTS	25-60	>1.1	<15
Medium medium sour	ANS	26-35	0.5-1.1	>15
Medium sour	Saudi Medium	26-35	>1.1	>15
Heavy sour	Maya	10-26	>1.1	>15
Syncrude (Canadian)	Long Lake	30-35	<0.5	<2
Dilbit (Canadian)	WCS	20-25	>3.0	>45

Note:
This domain corresponds to attributes **CRUDE**, **CRUDE_I** and **CRUDE_D** in the PMM.

Figure 5.7: Refinery Inputs (Other)

Attribute		Input Category and Stream
Main Attrib.	Sub-Attrib.	
REF_INP	UNF_OIL	**Unfinished Oils**
		Heavy naphtha
		Kerosene
		Vacuum gas oil (FCC feed)
		Resid
	BLN_STK	**Blendstocks (Petroleum-based)**
		I-butane
		N-butane
		Natural gasoline
		Alkylate
		Iso-octane
		Iso-octene
		Pyrolysis gasoline
	ALT_FUL	**Blendstocks (Alternative fuels)**
		Ethanol (for E10)
		Ethanol (for E85)
		Bio-diesel (FAME)
		Renewable diesel
		FT naphtha
		FT kerosene
		FT diesel

Figure 5.8: Refinery Processes

Attribute	Refinery Processes
CDU	**Crude Oil Distillation**
	Atmospheric crude unit
	Vacuum crude unit
UNIT	**Residual Oil Upgrading**
	Coking, delayed
	Coking, fluid bed
	Resid hydrocracking
	Solvent deasphalting
UNIT	**Cracking (current technology)**
	Catalytic cracking (FCC)
	Hydrocracking: distillate
	Hydrocracking: gas oil
	Hydrocracking: resid
UNIT	**Upgrading**
	Alkylation
	Dimer/Poly
	Isomerization (C4/C5/C6)
	Catalytic reforming: Low Press
	Catalytic reforming: Hi Press
UNIT	**Hydrotreating**
	FCC feed hydrofining
	FCC naphtha hydrotreating
	Reformer feed hydrotreating
	Benzene saturation
	Jet fuel hydrotreating
	Distillate hydrotreating
	Distillate dearomatization
	Resid hydrotreating
	Green diesel production
UNIT	**Splitting/Fractionation**
	Reformer feed splitter
	FCC naphtha splitter
	Debutanizer
	Depentanizer
UNIT	**Non-fuel-producing Operations**
	Aromatics extraction
	Lube and wax production
	Asphalt production
	Sulfur recovery/production
UTIL	**Refinery Utilities**
	Hydrogen production
	Hydrogen recovery
	Refinery fuel
	Steam generation
	CHP generation

Figure 5.9: Refinery-Produced Products[1]

Attributes		Product Category and Product	Blending Method	
Main	Sub-Att		Spec.	Recipe
PROD	GASB	**Motor Gasoline[2]**		
		E10 Blends		
		Conventional (CBOB)	X	
		Reformulated: federal (RBOB)	X	
		Reformulated: Calif. (CaRBOB)	X	
		E15 Blends		
		Conventional (CBOB)	X	
		Reformulated: federal (RBOB)	X	
		Reformulated: Calif. (CaRBOB)	X	
PROD	DIST	**Distillate Fuel**		
		Jet fuel (kero)	X	
		Kerosene	X	
		ULSD	X	
		EPA diesel	X	
		CaRB diesel	X	
		Bunker diesel	X	
		Heating oil (No. 2)	X	
PROD	RESID	**Residual Fuel**		
		Low sulfur resid (0 - 0.3)	X	
		Med sulfur resid (0.3 1.0)	X	
		High sulfur resid (> 1.0)	X	
PROD	REC_PROD	**Other Products**		
		LPG		X
		BTX		X
		Benzene		X
		Av Gas		X
		Asphalt and road oil		X
		Lubes and waxes		X
		Petroleum coke		
		Sulfur		X
PROD	REC_PROD	**Petrochemical Feedstocks**		
		Propylene/propane		X
		Butanes/pentanes		X
		Naphtha		X
		Gas oil		X

Notes:

1 This domain does not include terminal-blended products, such as finished gasolines and E85.

2 Gasolines are represented by type , but not by grade (e.g., REG, PRM) within type.

Figure 5.10: Product Blending Specifications

Attribute	Product Category	Blend Properties and Specifications
QUAL_G	Gasoline	Octane (Res) Octane (Mot) RVP Sulfur Benzene Aromatics T_{10} T_{50} T_{90}
QUAL_D	Distillates	Sulfur Cetane Number Smoke Point Flash Point Pour Point
QUAL_R	Residual Fuels	Sulfur Specific Gravity Viscosity

Note:
The T10, T50, and T90 specifications apply only to CaRFG.

Figure 5.11: Alternative Fuels Inputs

Attribute	Feedstock
REN_FEED	Starch - corn Starch - other Sugar cane Biomass oils Cellulosic biomass Sep. food waste Landfill waste
ALT_FEED	Coal Natural gas Biomass oils

Figure 5.12: Renewable Fuels Types in EISA

Attribute	Fuel Type	Code
RFS_CAT	Renewable fuel	R
	Advanced biofuel	A
	Biomass-based diesel	B
	Cellulosic ethanol	C
	Cellulosic distillate	7

Note:

The *Fuel Type Codes* denote the applicable renewable fuel type defined in EISA.
R = Renewable fuel, **A** = Advanced biofuel,
B = Biomass-based diesel, **C** = Cellulosic biofuel, 7 = Cellulosic Bio-diesel

Figure 5.13: RFS2 Pathways for Producing Renewable Fuels

	Pathway			Fuel Type
	Feedstock	Production Process	Renewable Fuel	(Note 1)
	Starch -- corn	Dry milling, meeting certain requirements	Ethanol	R
RFS_PATH	Starch -- corn	Wet milling, meeting certain requirements	Ethanol	R
	Starch -- agricultural residues and annual cover crops	Fermentation, with specified sources of process energy	Ethanol	R
	Sugar cane	Fermentation	Ethanol	A
	Cellulosic biomass	Any	Ethanol	C
	Starch -- corn	Fermentation, with specified sources of process energy	Butanol	R
	Bio-mass oils	Trans-esterification	Bio-diesel	B
	Bio-mass oils	Hydrotreating, *excluding* processes that co-process renewable biomass and petroleum	Renewable diesel	B
	Bio-mass oils	Hydrotreating, *including* only processes that co-process renewable biomass and petroleum	Renewable diesel	A
	Cellulosic biomass	Any	Cellulosic bio-diesel	7
	Cellulosic biomass	Fischer-Tropsch processes (BTL)	Cellulosic naphtha	C
	Non-cellulosic food waste	Any	Ethanol	A
	Non-cellulosic food waste	Any	Renewable diesel	A
	Landfills, sewage and waste treatment plts, manure digesters	Any	Bio-gas	A

Notes:

1. The *Fuel Type codes* denote the applicable renewable fuel type defined in EISA, and the corresponding RIN type.
R = Renewable fuel, **A** = Advanced biofuel, **B** = Biomass-based diesel, **C** = Cellulosic biofuel, **7** = Cellulosic Bio-diesel
Type 7 RINs may be used to satisfy either Type B or Type C requirements.

2. *Cellulosic biomass* comprises agricultural residues; slash, forest thinnings, and forest product residues, annual cover crops; switchgrass and miscanthus; cellulosic components of separated food wastes; and cellulosic components of separated municipal solid waste.

3. *Bio-mass oils* comprise soy bean oil; oil from annual cover crops; algal oil; biogenic waste oils/fats/greases; and non-feed grade corn oil.

Figure 5.14: Transport Modes

Attribute	Transport Mode
TR_MODE	Crude oil tanker Product tanker Product tanker -- Jones Act Barge Crude oil pipeline Refined product pipeline LPG pipeline Natural gas pipeline Rail

Regionality

There are many possible regional aggregation approaches that could be chosen to represent petroleum refining operations in the United States. The PMM uses the Petroleum Administration for Defense Districts (PADD) regions because that is how much of the available refinery data is provided. However, other regionalization approaches may make more sense when trying to model the behavior of the domestic liquid fuels market. Although one such alternate regionalization approach is described below, other approaches may be tested during the prototyping phase. For that reason, the approach described below may not be the final approach taken for the LFMM.

Domestic Refinery Region Disaggregation

As **Figure 5.5** indicates, the LFMM will be designed so that the number of refining regions can be easily changed to best meet EIA's evolving modeling needs. For example, one option will be for the LFMM to represent refining operations in eight refining regions:

- Domestic regions
  - PADD 1
  - PADD 2 Great Lakes
  - PADD 2 Central
  - PADD 3 Gulf Coast
  - PADD 3 Inland
  - PADDs 4 & 5 (ex California)
  - California
- Off-shore region: Eastern Canada/Caribbean

This set of refining regions differs from the five region representation – the five PADDs – represented in NEMS and the PMM. The rationale for this proposed set of LFMM refining regions is as follows.

PADD 2 refineries are divided into two proposed sub-regions – *Great Lakes* and *Central* – whose refinery populations are shown in **Figure 5.15**. As the figure indicates, the characteristics of the refining aggregates in the two sub-regions differ significantly.

The *Great Lakes* region encompasses PADD 2 refineries that have, or soon will have, access to pipeline supplies of Canadian oil sands crudes (WCS, dilbit, SCO, etc.). The Great Lakes refineries have about two-thirds of the crude running capacity in PADD 2, and about 82 percent of their total crude running capacity is in coking refineries. The Great Lakes refineries currently import just over half of their total crude run, with much of the import volume coming from Canada (both conventional and oil sands crudes). They primarily serve local markets and compete in these markets with PADD 3 refineries.

Figure 5.15: Estimated Crude Running and Coking Capacity in PADD 2 Refineries, as of Jan. 2008

Company & Location			Com-	Distillation			Crude Oil Import in 2006				
							%	API	Sp.	Volume	% of
Company	Site	State	plexity	Atmos	Vacuum	Coking	Sulfur	Grv.	Grv.	(K b/d)	Dist. Cap
PADD 2			**9.7**	**3,640,100**	**1,457,275**	**379,370**	**1.80**	**28.0**	**0.887**	**1,501**	**41**
Midwest Great Lakes			**9.7**	**2,362,400**	**1,025,700**	**288,320**	**1.84**	**27.3**	**0.891**	**1,225**	**52**
Citgo Petroleum Corp.	Lemont (Chicago)	IL	9.5	158,650	71,250	36,000	2.82	24.7	0.906	134	84
ExxonMobil Refg & Supply Co	Joliet	IL	10.0	240,000	121,500	56,000	0.62	31.6	0.868	207	86
Marathon Petroleum Co.	Robinson	IL	10.1	192,000	61,900	27,900	0.86	34.9	0.850	63	33
WRB Refining LLC	Wood River	IL	8.6	306,000	119,000	16,000	2.24	27.6	0.889	147	48
BP PLC	Whiting	IN	10.4	405,000	189,000	34,500	2.30	26.3	0.897	130	32
Marathon Ashland Petro LLC	Detroit	MI	7.3	100,000	48,500		1.77	28.0	0.887	65	65
Flint Hills Resources	Rosemount	MN	9.5	323,000	185,250	63,720	2.54	20.8	0.929	222	69
Marathon Ashland Petro LLC	Saint Paul Park	MN	10.7	70,000	30,400		1.25	29.6	0.879	47	67
BP PLC	Toledo	OH	10.2	160,000	71,500	33,500	3.22	20.9	0.928	52	33
Husky Energy Corp.	Lima	OH	10.1	161,500	49,400	20,700	0.37	33.3	0.859	91	65
Marathon Petroleum Co.	Canton	OH	8.0	73,000	28,500		2.13	30.8	0.872	23	32
Sunoco Inc.	Toledo	OH	10.4	140,000	30,000		0.18	40.1	0.825	24	15
Murphy Oil U.S.A. Inc.	Superior	WI	8.6	33,250	19,500		2.25	25.3	0.903	20	60
Midwest Central			**9.6**	**1,277,700**	**431,575**	**91,050**	**1.54**	**31.4**	**0.869**	**252**	**20**
Countrymark Cooperative Inc.	Mount Vernon	IN	9.1	23,500	8,000						
Coffeyville Resources R&M	Coffeyville	KS	9.2	100,000	50,000	19,000	1.08	25.7	0.900	21	21
Frontier El Dorado Refg Co.	El Dorado	KS	12.3	110,000	41,000	18,750	2.44	25.1	0.903	19	17
NCRA	McPherson	KS	15.0	82,700	35,400	20,800	3.14	20.9	0.929	5	6
Marathon Petroleum Co.	Catlettsburg	KY	11.5	222,000	114,500		1.71	33.3	0.859	101	45
Somerset Refinery Inc.	Somerset	KY	3.1	5,500							
Tesoro West Coast Co.	Mandan	ND	7.8	58,000			1.20	35.0	0.850	1	2
ConocoPhillips Inc.	Ponca City	OK	10.7	187,000	80,000	24,000	1.71	24.6	0.907	43	23
Sinclair Oil Corp.	Tulsa	OK	6.8	70,000	25,175		2.00	21.6	0.924		
Sunoco Inc.	Tulsa	OK	5.3	85,000	30,000	8,500					
Valero Energy Corp.	Ardmore	OK	10.2	91,500	32,000		1.35	34.9	0.850	34	37
Wynnewood Refining Co.	Wynnewood	OK	8.1	52,500	15,500		0	32	0.866		
Valero Energy Corp.	Memphis	TN	6.7	190,000			0.18	43.2	0.810	28	15

Sources: Capacity derived from "2007 Worldwide Refinery Survey," *Oil & Gas Journal*, Dec. 18, 2007;and DOE 2007 Refinery Capacity Survey (DOE website).

The *Central* region encompasses the balance of PADD 2 refineries – those that do not have access (currently or prospectively) to Canadian oil sands crudes. The Central refineries have about one-third of the crude running capacity in PADD 2. Only about 44 percent of Central crude running capacity is in coking refineries. Correspondingly, the aggregate crude slate in the Central region is considerably lighter and sweeter than that of the Great Lakes region. The Central refineries currently import about 20 percent of their total crude run, with most of the import volume coming from off-shore sources. The Central refineries primarily serve local markets.

The LFMM proposes to divide *PADD 3* refineries into two sub-regions – *Gulf Coast* and *Inland.* The proposed refinery populations are shown in **Figure 5.16**. As the figure indicates, the characteristics of the refining aggregates in the two sub-regions differ significantly from one another, and each is relatively homogeneous.

The *Gulf Coast* sub-region encompasses nearly 90 percent of the crude running capacity in PADD 3. In turn, about 90 percent of the Gulf Coast crude running capacity is in coking refineries, with the balance in cracking refineries (labeled **Gulf Coast Other** in **Figure 5.16**). The Gulf Coast refineries currently import about 70 percent of their total crude run. The imported crudes run by the coking refineries are considerably heavier and more sour than the crude slates run by either the Gulf Coast cracking refineries or the Inland refineries. The Gulf Coast cracking refineries tend to be smaller than the coking refineries, and most are located in close proximity to the centers of Gulf Coast coking refinery capacity. Much of the Gulf Coast region's product volume goes to PADD 1 and PADD 2, mainly via large common-carrier pipelines.

The *Inland* sub-region is much smaller, encompassing only about 10 percent of the crude running capacity in PADD 3. The Inland region comprises mainly cracking refineries: only 11 percent of the Inland crude running capacity is in coking refineries. The Inland refineries import only 12 percent of their total crude run, and the imported crudes are considerably lighter and sweeter than the imported crudes run by the Gulf Coast refineries. The Inland refineries tend to be smaller and less complex than the Gulf Coast refineries. Much of the Inland region's product volume goes to local or niche markets within the PADD.

Figure 5.16: Estimated Crude Running and Coking Capacity in PADD 3 Refineries, as of Jan. 2008

Company & Location			Com-	Distillation			Crude Oil Import in 2006				
							%	API	Sp.	Volume	% of
Company	Site	State	plexity	Atmos	Vacuum	Coking	Sulfur	Grv.	Grv.	(K b/d)	Dist. Cap
PADD 3			**10.7**	**8,440,162**	**3,854,206**	**1,316,940**	**1.90**	**28.3**	**0.885**	**5,624**	**67**
Gulf Coast Total			**10.8**	**7,488,902**	**3,532,531**	**1,287,440**	**1.98**	**27.9**	**0.888**	**5,240**	**70**
Gulf Coast Coking			**11.2**	**6,640,450**	**3,263,850**	**1,287,440**	**2.02**	**27.3**	**0.891**	**4,746**	**71**
Hunt Refining Co.	Tuscaloosa	ALn	8.7	35,000	15,000	14,000	3.53	23.7	0.912	34	97
Chalmette Refining LLC	Chalmette	LAg	11.7	192,500	112,000	38,000	2.72	19.0	0.940	89	46
Citgo Petroleum Corp.	Lake Charles	LAg	9.8	440,000	200,000	88,200	1.31	23.7	0.911	252	57
ConocoPhillips	Westlake	LAg	9.2	239,000	106,200	60,840	2.61	23.0	0.916	165	69
ConocoPhillips	Belle Chasse (Allia	LAg	10.8	247,000	92,000	25,200	0.48	34.1	0.855	114	46
ExxonMobil Refg & Supply Co	Baton Rouge	LAg	10.2	503,000	231,500	114,000	1.38	28.7	0.883	289	57
Marathon Ashland Petro LLC	Garyville	LAg	13.4	245,000	127,300	38,000	3.18	24.7	0.906	179	73
Motiva Enterprises LLC	Norco	LAg	10.1	220,000	78,000	21,380	0.26	32.8	0.861	115	52
Motiva Enterprises LLC	Convent	LAg	10.1	235,000	104,000	12,520	2.65	30.7	0.872	217	92
Valero Refining Co.	Norco	LAg	11.4	186,000	130,000	70,400	3.09	20.6	0.930	97	52
ChevronTexaco Corp.	Pascagoula	MSg	11.2	330,000	240,000	98,000	2.74	23.4	0.913	336	102
BP PLC	Texas City	TXg	15.9	475,000	237,000	43,000	0.46	37.0	0.840	102	21
Citgo Petroleum Corp.	Corpus Christi	TXg	13.8	156,750	73,625	37,800	1.13	30.5	0.873	219	140
ConocoPhillips	Sweeny	TXg	12.2	247,000	125,500	70,900	1.77	22.2	0.920	240	97
ExxonMobil Refg & Supply Co	Baytown	TXg	10.0	567,000	270,000	85,000	1.86	29.7	0.878	493	87
ExxonMobil Refg & Supply Co	Beaumont	TXg	12.1	348,500	143,000	48,000	1.56	33.0	0.860	280	80
Flint Hills Resources	Corpus Christi	TXg	10.2	279,300	83,125	12,600	0.70	37.3	0.838	170	61
Lyondell-Citgo Refining LP	Houston	TXg	10.6	282,600	191,000	98,500	2.40	17.8	0.948	264	93
Motiva Enterprises LLC	Port Arthur	TXg	9.4	285,000	124,000	50,000	2.47	31.9	0.866	264	93
Pasadena Refining System	Pasadena	TXg	7.4	117,000	41,000	12,000	0.13	37.8	0.836	69	59
Shell Deer Park Refg Co.	Deer Park	TXg	9.9	329,800	169,600	81,600	2.91	23.5	0.913	298	90
Valero Energy Corp.	Port Arthur	TXg	12.5	250,000	145,000	100,000	3.39	20.6	0.930	105	42
Valero Energy Corp.	Texas City	TXg	9.7	225,000	130,000	50,000	2.66	27.2	0.892	194	86
Valero Energy Corp.	Corpus Christi	TXg	17.3	205,000	95,000	17,500	1.93	30.6	0.873	161	79
Gulf Coast Other			**7.3**	**848,452**	**268,681**	**0**	**1.56**	**33.7**	**0.856**	**494**	**58**
Gulf Atlantic Operations	Mobile Bay	ALg	2.5	20,000	15,000						
Shell Chemical	Saraland (Mobile)	ALg	6.2	85,000	28,000		0.11	44.7	0.803	53	62
Calcasieu Refining Co.	Lake Charles	LAg	1.0	32,000			0.13	44.4	0.804	7	22
Murphy Oil U.S.A. Inc.	Meraux	LAg	8.9	125,000	50,000		1.53	32.1	0.865	48	38
Placid Refining Co.	Port Allen	LAg	6.2	55,000	20,900						
Shell Chemical	Saint Rose	LAg	2.0	55,000	28,000		0.05	43.3	0.810	40	73
Valero Refining Co.	Krotz Springs	LAg	7.0	83,000	36,000						
Marathon Ashland Petro LLC	Texas City	TXg	8.4	72,000			0.13	41.3	0.819	21	29
Total SA	Port Arthur	TXg	7.8	231,452	51,781		2.35	29.1	0.881	277	120
Valero Energy Corp.	Houston	TXg	11.6	90,000	39,000		0.30	39.4	0.828	48	53
Inland			**9.8**	**951,260**	**321,675**	**29,500**	**1.16**	**32.3**	**0.864**	**116**	**12**
Cross Oil & Refining Co. Inc.	Smackover	AR	10.3	7,000	3,000						
Lion Oil Co.	El Dorado	AR	8.5	70,000	27,075		1.69	33.8	0.856	24	34
Calumet Lubricants Co.	Cotton Valley	LAn	3.3	9,500							
Calumet Lubricants Co.	Princeton	LAn	18.3	9,500	8,500						
Calumet Lubricants Co.	Shreveport	LAn	11.3	35,000	15,000						
Ergon Refining Inc.	Vicksburg	MSn	8.8	23,000	10,200		0.62	20.1	0.933	19	83
Giant Refining Co.	Bloomfield	NM	6.4	18,600							
Giant Refining Co.	Gallup	NM	8.3	26,000							
Holly Corp	Artesia	NM	10.4	85,000	25,000						
Age Refining & Manfacturing	San Antonio	TXi	2.5	12,000							
Alon USA LP	Big Spring	TXi	8.5	70,000	24,000						
Delek Refining Ltd	Tyler	TXi	8.8	60,000	15,000	6,500					
Valero Energy Corp.	Sunray	TXi	9.0	166,660	53,200						
Valero Energy Corp.	Three Rivers	TXi	13.4	96,000	35,000		0.69	35.9	0.845	48	50
Western Refining Inc	El Paso	TXi	5.5	117,000	34,700						
WRB Refining LLC	Borger	TXi	14.3	146,000	71,000	23,000	1.97	34.2	0.854	25	17

Sources: Capacity derived from "2007 Worldwide Refinery Survey," *Oil & Gas Journal*, Dec. 18, 2007;and
DOE 2007 Refinery Capacity Survey (DOE website).

In the proposed LFMM, *California* will be represented as a separate refining region because the California refining sector constitutes about two-thirds of total refining capacity in PADD 5, and is unique in many respects. The crude slate of California refineries includes significant volumes of heavy, sour California crudes, which are not run anywhere else. California has its own standards and compliance mechanisms for gasoline and diesel fuel, which are substantially more stringent than the Federal standards. California refineries are subject to many other State regulations that constrain existing refining operations and deter investment in new capacity. Because of the unique crude slate and product standards that they deal with, California refineries have high complexity and operating capabilities not found in other U.S. refineries. Finally, California refineries have significantly higher marginal costs of production and higher per-barrel energy use than other U.S. refineries.

PADDs 4 and 5 (ex California) will be represented in the proposed LFMM as a single refining region because (1) total refining capacity and petroleum product production in these areas are relatively small (about 1.9 M Bbl/day, about the size of California alone), (2) refining capabilities in these areas are comparable to one another, but substantially different from those in California, and (3) with respect to product distribution, PADDs 4 and 5 have relatively little interaction with California. (The Puget Sound refining center in PADD 5 does supply some gasoline blendstock volumes to California refineries. This flow can be represented in the LFMM.)

The *Off-shore (Eastern Canada/Caribbean)* refineries are a handful of large, nearby off-shore refineries (i.e., refineries in Maritime Canada, the Virgin Islands, and the Caribbean) that produce large volumes of refined products to U.S. specifications. These short-haul refineries will be represented as a refining region because they are an integral part of the U.S. petroleum product supply system. Essentially all their exports go to the U.S., and collectively, they account for about one-third of U.S. gasoline imports and about two-thirds of distillate fuel imports. More importantly, by virtue of their location and capital stock, they are likely to retain their competitive advantage as suppliers to U.S. East Coast markets relative to more distant export refineries, even the large, complex, and low-cost new refineries in East Asia.[8]

The other sources of U.S. petroleum product imports – e.g., EU refineries – will be represented simply by import supply curves. (Presumably, these supply curves would be generated by the International Energy Module of NEMS or some other EIA model of world petroleum markets.) The supply curves are in the set of matrix column strips called **Import Finished Products** (**Figure 6.8**).

[8]This refining region could be represented in NEMS as either (1) aggregate refining capacity sufficient to supply reported U.S. imports of petroleum products from these refineries or (2) aggregate refining capacity equal to the reported capacity of these refineries, with petroleum product output divided between exports to the U.S. and in-region supply.

International Treatment/Interrelationships

The LFMM interface with international representation in NEMS for crude oil supply will be the same as with the current NEMS-PMM approach. The LFMM will input a computed world oil price and world supply curves from the International Energy Module.

In the past, there has been concern about the tendency within the PMM to rely extensively on heavier high sulfur crude, even to the extent that processing investment is required for processing the crude. This is likely related to some extent to the crude quality differentials, which the PMM sees from the International Energy Module. In the LFMM, as a greater volume of heavier, high sulfur crude is processed (demanded), the supply relationships should respond with increased price. More importantly, the differential between heavy and light crude should decline. (With no change in total global crude demand, heavy crude should respond with upward pricing and light crude with downward pricing).

Relationship to NEMS Demand Region Disaggregation

The process for relating the LFMM refining regions to the NEMS demands regions will remain the same as in the PMM. New sharing factors will need to be established, however, to reflect the change in the refining region aggregation.

Classification of resource inputs:

Crude Oil Categories and Regional Crude Oil Slates

Crude Oil Categories

As **Figure 5.6** indicates, the LFMM will represent seven crude oil categories: five applying to conventional crude oils and two to crude oils (bitumens) produced from Canadian oil sands. The five categories of conventional crude oils are standard classifications based on crude oil density (API gravity) and sulfur content. They are the same as those used in the PMM, and they apply to both domestic and imported crude oils.

The two Canadian oil sand categories represent *synthetic crude oil (SCO)*, produced by field upgrading (coking or hydrocracking) of bitumen, and *diluted bitumen (dilbit)*.[9,10]

Crude oil categories for Canadian oil sand crudes are needed in the proposed LFMM because:

[9]*Dilbit* is a 25/75 mixture of light naphtha and bitumen. The light naphtha diluent is added to enable the bitumen to flow through a pipeline. The diluent is either processed in the refinery or separated and re-cycled to Alberta for re-use.

[10]It may prove useful to add a third Canadian oil sands crude: Western Canadian Select (WCS). WCS is a specification-blended mixture of SCO, bitumen, and conventional heavy crude, being offered by certain Canadian producers as a standardized crude oil.

- Canadian oil sand crudes differ from conventional crudes in their assay properties and refinery processing requirements.

  SCOs contain essentially no vacuum resid material (coker feed) and have low sulfur content. Bitumens contain a large volume fraction of vacuum resid and have high sulfur content. Both materials are hydrogen-deficient in all fractions, with highly aromatic vacuum gas oil (FCC feed) and distillate fractions, and high metals contents. Hence, they require intensive conversion and hydrotreating.

- Canadian oil sand crudes are an increasingly important component of U.S. crude imports.

  Oil sand crudes are entering the U.S. in rapidly increasing volumes, with most of the volume going to the PADD 2 Great Lakes region. Canada's production of oil sand crudes is slated to increase rapidly in the next decade, and most of it will flow to the U.S. By 2020, oil sand crudes may constitute more than 50 percent of the aggregate crude slate of PADD 2 refineries and two-thirds of the aggregate crude slate of the Great Lakes refineries.

Trends in the Quality of the U.S. Refinery Crude Slate

In 2008, the average sulfur content of the aggregate U.S. crude slate was 1.47 percent by weight; the average API gravity was 30.21.[11] In PADD 1, the aggregate crude slate is considerably lighter and sweeter than the national average; in PADD 3, the aggregate crude slate is heavier and more sour.

For more than twenty years, the aggregate crude slate in the U.S. as a whole and in most PADDs has exhibited a gradual but strong trend toward higher sulfur content and lower API gravity, as shown in **Figure 5.17** and **Figure 5.18**. Over the period 1985-2008, the average annual rates of change for the aggregate U.S. crude slate are about *0.023 percent/weight sulfur/year* and *-0.094 API/year*.

However, as **Figure 5.17** and **Figure 5.18** indicate, within this long-term trend, the year-to-year changes in crude sulfur content and API gravity exhibit considerable variation over time and across regions. **Figure 5.19** quantifies this variation. For the period 1985-2008, **Figure 5.19** shows (1) the average annual rates of change in average sulfur content and API gravity of the aggregate crude slates in each PADD and for the U.S. as a whole and (2) the average and maximum absolute values of the year-to-year changes in these properties in each PADD and for the U.S. as a whole.

[11] As **Figure 5.6** indicates, sour crudes are usually defined as having sulfur content > 1.1 percent by weight. However, in practice, the average sulfur content of the sour crudes processed in U.S. refineries must be considerably higher than that in order for the average sulfur content of the entire crude slate to be 1.47 percent by weight. Indeed, most of the sour crudes have sulfur contents in the 2-3 percent by weight range.

Representation of Regional Crude Oil Slates

The LFMM will represent domestic and imported crude oil supplies by means of supply curves – one for each combination of crude oil category and refining region, and separately for imported and domestic crudes. These supply curves are in the matrix column strips called **Crude Oil Imports and Crude Oil Domestic** in Section 2 of the matrix block diagram (**Figure 6.5**). The total volumes of imported and domestic crudes available to the U.S. for each crude oil category will be subject to control by specified upper and lower bound values.

In addition, the composition (by crude category) of each regional crude slate will be subject to control by special constraints that limit the average sulfur content and API gravity of the aggregate crude slate in each region. These special constraints are in the matrix row strip **Δ Crude Oil Quality** in **Figure 6.5**.

Figure 5.17: Regional Trends in Crude Oil Sulfur Content

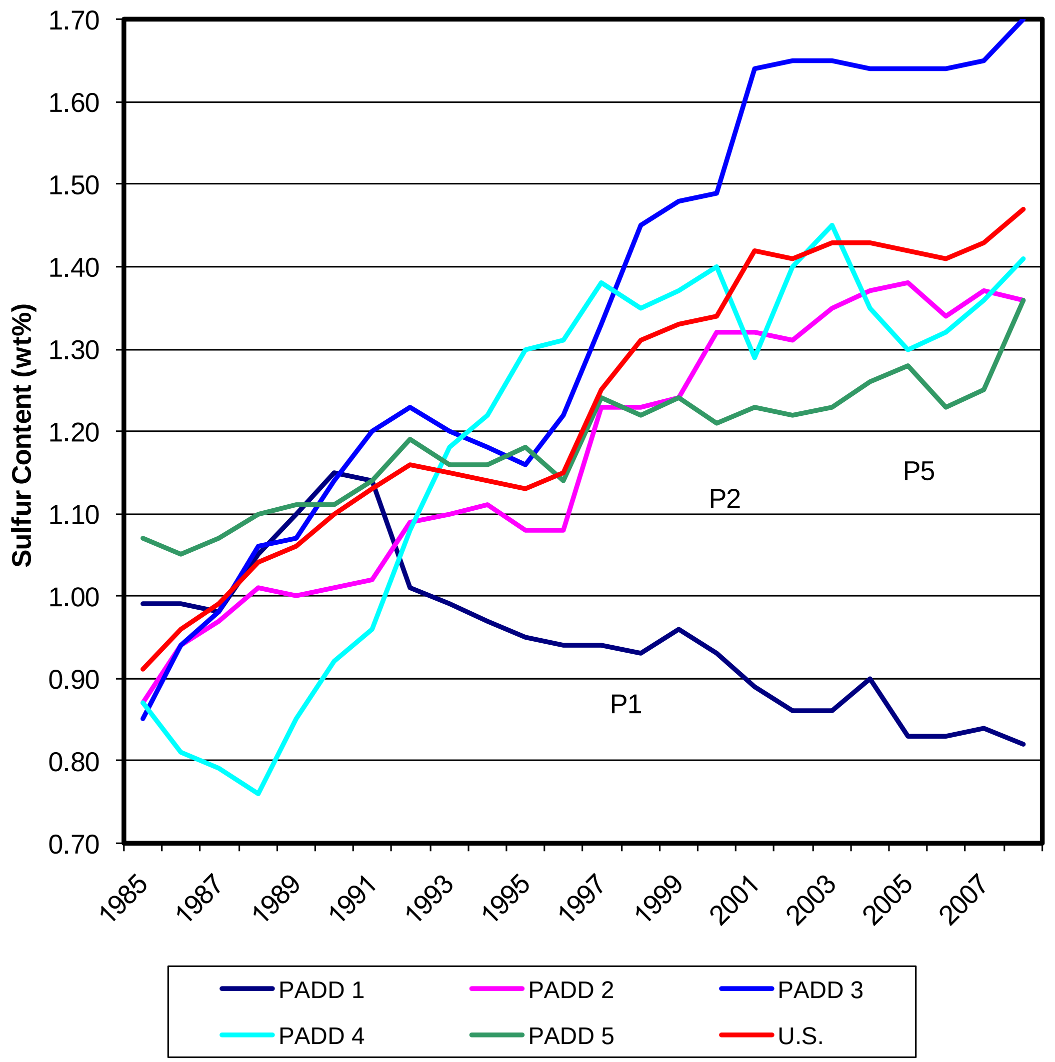


Figure 5.18: Regional Trends in Crude Oil API Gravity

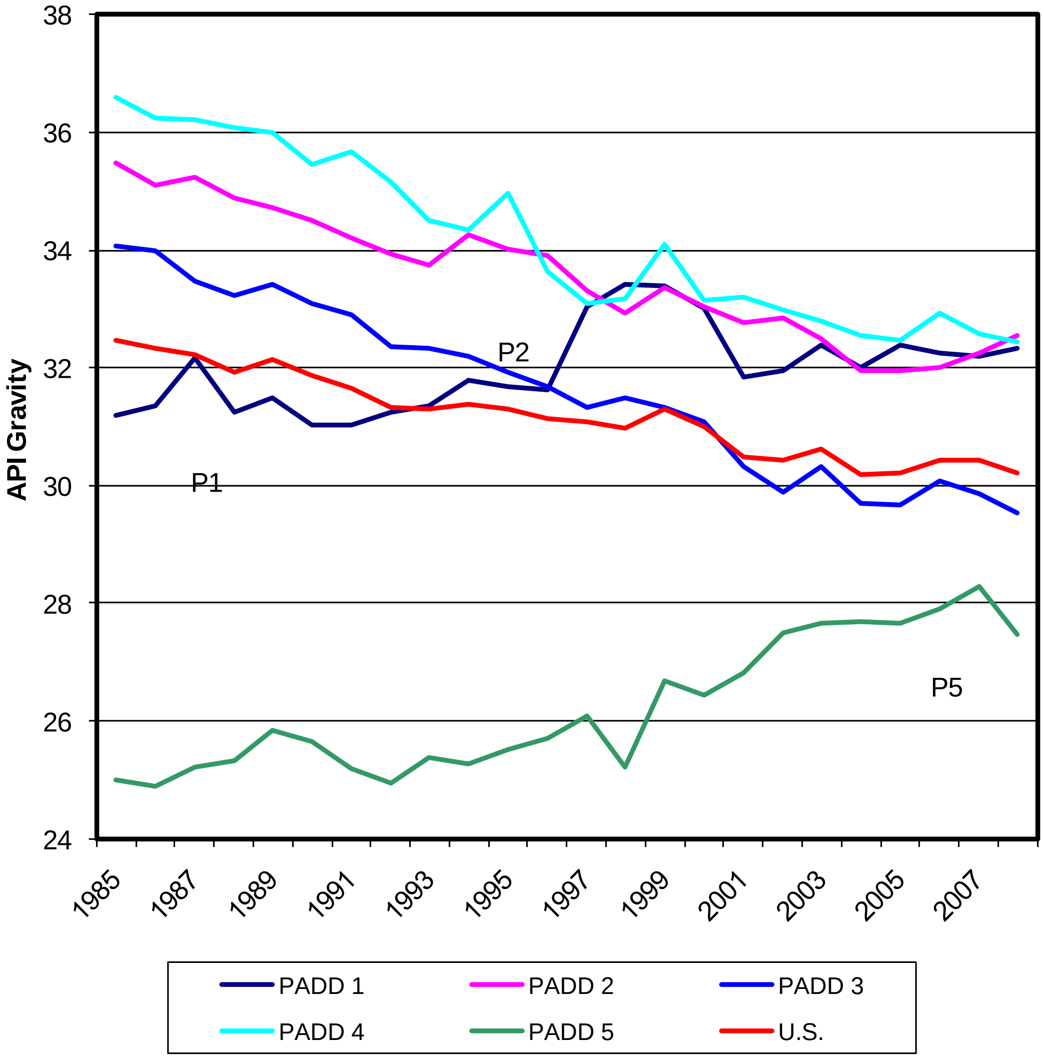


Figure 5.19: Average Annual Rates of Change and Year-to-Year Changes in Crude Oil Sulfur Content and API Gravity, by PADD, for the Period 1985 to 2008

	PADD 1		PADD 2		PADD 3		PADD 4		PADD 5		U.S.	
Annual Changes	Sulfur (wt %)	API Gravity	Sulfur (wt %)	API Gravity	Sulfur (wt %)	API Gravity	Sulfur (wt %)	API Gravity	Sulfur (wt %)	API Gravity	Sulfur (wt %)	API Gravity
1985-2008 Average	-0.007	0.048	0.020	-0.123	0.035	-0.189	0.023	-0.174	0.012	0.102	0.023	-0.094
Year-to-Year Absolute Value												
Average	0.029	0.373	0.030	0.278	0.044	0.303	0.058	0.387	0.030	0.375	0.030	0.192
Maximum	0.130	1.400	0.150	0.610	0.150	0.770	0.120	1.330	0.110	1.450	0.100	0.500

In the LFMM, the limit values (RHS values) on sulfur content and API gravity would be specified for each refining region, for each year in the NEMS time horizon. Subject to these limits, the average crude sulfur content and API gravity in each refining region returned by the LFMM could change from year to year. At EIA's choice, the regional time profiles of average crude sulfur content and API gravity could be consistent with either (1) the historical rates of change shown in **Figure 5.19** or (2) EIA projections of average crude oil quality in future years. The regional limit values for sulfur content and API gravity would reside in a table accessed by the LFMM matrix generator. This table would be updated for each year by the NEMS Integrating Module.

This element of the model design would allow the LFMM to determine the crude slate in each refining region and each year endogenously, in response to (1) the set of exogenous crude supply curves, (2) limits on aggregate imported and domestic crude availability, and (3) refining economics, subject to user-specified limits on the average sulfur content and API gravity of the crude slate.

This approach (1) recognizes the historical evolution of the U.S. and regional crude slates, (2) minimizes the likelihood of large year-to-year changes in crude oil slate and (3) minimizes the consequent incentives for refinery investment made solely to process large new volumes of low quality crude oil in a given year, investment which is then "stranded" in future years. This third consideration will also be mitigated by the multi-period planning approach to be used in the LFMM as explained in Chapter 6.

Alternative Fuels Production

The alternative fuels production segment of the LFMM will represent operation of existing and possible future commercial-scale facilities for producing alternative fuels:

- Renewable fuels, as defined by EISA
- CTL and GTL liquid fuels
- Green diesel

This segment of the LFMM will represent the primary pathways (feed → process → product) for producing renewable fuels and other alternative fuels from specified biomass or hydrocarbon feedstocks. The sources of supply of these feedstocks are in sectors exogenous to those represented in the LFMM. Hence, the supplies of these feedstocks will be represented in the LFMM by supply functions (price/volume relationships) generated by other NEMS modules.

Representation of Renewable Fuels

The LFMM will contain representations of renewable fuels production in the various alternative fuel supply regions (i.e., Census Regions). The representations will cover all renewable fuels types defined in EISA and all pathways for producing them established and certified by EPA in the RFS2 rule.[12] **Figure 5.20** shows the certified pathways for producing the various types of renewable fuels defined by EISA.

The LFMM renewable fuels representations will consist of (1) simple conventional process representations of commercial facilities for the pathways now in commercial use – corn ethanol production (wet milling and dry milling), sugar cane ethanol production, and bio-diesel production and (2) place-holder representations for the remaining pathways, which are not yet in commercial use.

The place-holder representations of potential future pathways will consist of small sets of input/output variables. The matrix columns corresponding to these variables will carry coefficients representing primary inputs and outputs. The inputs and outputs for each pathway will include technical, economic, and emissions parameters, as well as the estimated or EPA-specified lifecycle GHG reduction associated with the pathway. The levels of the input/output variables in solutions returned by the LFMM will denote production volumes of the given renewable fuel via the given process in a given region.

[12] EPA's certification of a pathway means that EPA has made a finding that renewable fuel produced by that pathway satisfies the relevant requirement in EISA for percentage reduction in lifecycle emissions of GHGs relative to a baseline hydrocarbon fuel.

Figure 5.20: Certified Pathways for Producing Renewable Fuels Under the RFS2 Rule

Renewable Fuel	Pathway: Feedstock	Pathway: Production Process	Fuel Type (Note 1)
Ethanol	Starch -- corn	*Dry milling,* using natural gas, biomass, or biogas for process energy, and meeting certain other requirements	R
	Starch -- corn	*Wet milling,* using biomass or biogas for process energy	R
	Starch -- agricultural residues and annual cover crops	Fermentation, using natural gas, biomass, or biogas for process energy	R
	Sugar cane	Fermentation	A
	Cellulosic biomass (Note 2)	Any	C
Butanol	Corn starch	Fermentation; dry milling using natural gas, biomass, or biogas for process energy	R
Bio-diesel and Renewable diesel	Bio-mass oils (Note 3)	Trans-esterification; hydrotreating, *excluding* processes that co-process renewable biomass and petroleum	B B
Bio-diesel and Renewable diesel	Bio-mass oils	Trans-esterification; hydrotreating, *including only* processes that co-process renewable biomass and petroleum	A A
Cellulosic distillates	Cellulosic biomass	Any	7
Cellulosic naphtha	Cellulosic biomass	Fischer-Tropsch processes (BTL)	C
Ethanol, renewable distillates and naphthas	The non-cellulosic portions of separated food wastes	Any	A
Bio-gas	Landfills, sewage and waste treatment plts, manure digesters	Any	A

Notes:

1. The *Fuel Type designators* denote the applicable renewable fuel type defined in EISA, and the corresponding RIN type.
   R = Renewable fuel, **A** = Advanced biofuel, **B** = Biomass-based diesel, **C** = Cellulosic biofuel, **7** = Cellulosic Bio-diesel
   Type 7 RINs may be used to satisfy either Type B or Type C requirements.
2. *Cellulosic biomass* comprises agricultural residues; slash, forest thinnings, and forest product residues, annual cover crops; switchgrass and miscanthus; cellulosic components of separated food wastes; and cellulosic components of separated municipal solid waste.
3. *Bio-mass oils* comprise soy bean oil; oil from annual cover crops; algal oil; biogenic waste oils/fats/greases; and non-feed grade corn oil.
4. Reference: 80 CFR, Section 1426, Table 1

In addition, the LFMM representation of capacity additions (discussed below) will include renewable fuels capacity for each pathway (with the associated capital investment) in each applicable region.

Finally, the representation will include constraints, in row strip **Policy (enviro)**, that impose EISA's annual mandate volumes for the various renewable fuels classes: total renewable fuels, advanced biofuels, cellulosic biofuels, and biomass-based diesel fuel.

Representation of CTL and GTL Production

The LFMM will contain place-holder representations in the various alternative fuels supply regions (i.e., Census Regions) of coal-to-liquids (CTL) and gas-to-liquids (GTL) processes.

CTL and GTL processes have been in commercial use for many years in various parts of the world. As a result, sufficient data are available in the literature to support development of fairly detailed representations of CTL and GTL process in the LFMM. However, CTL and GTL technologies remain uneconomical in the U.S., except under unusual circumstances, and current Federal policies and programs do not promote significant expansion of commercial CTL and GTL production.

Consequently, at least for the moment, the LFMM representation of CTL and GTL production will consist of small sets of input/output variables. The matrix columns corresponding to these variables will carry coefficients representing the primary inputs and outputs of representative commercial processes. The inputs and outputs will include technical, economic, and emissions parameters. The levels of the input/output variables in solutions returned by the LFMM will denote production volumes of CTL or GTL (as the case may be) in a given region.

In addition, the LFMM representation of capacity additions (discussed below), will include CTL and GTL capacity (with the associated capital investment), in each applicable region.

Representation of Green Diesel Production

The LFMM will contain a place-holder representation in each refining region of *refinery-based* production of green diesel – a hydrocarbon diesel fuel blend stock produced by hydro-treating biomass feedstocks, such as palm oil, rapeseed oil, other vegetable oils, and waste animal fats, within a refinery or other large process complex.

Green diesel production is in an early stage of commercial development.

- Neste Oil has a proprietary green diesel process, NExBTL™. It has a NExBTL unit in operation at its Porvoo, Finland refinery, producing about 3.5 K Bbl/day of green diesel blend stock. Neste has two other units under construction:
    - Port of Rotterdam, slated to produce about 16 K Bbl/day
    - Singapore, slated to produce about 13 K Bbl/day

- UOP and ENI jointly offer a similar process, Ecofining™. ENI has announced construction of one Ecofining unit in Europe; this unit is scheduled for start-up in 2010.

There is no commercial production of green diesel in the U.S. at this time.

Clearly, the green diesel processes are new and commercial experience with them is limited. The technical and economic data on these processes available from the technology developers and from public sources is not yet sufficient for representing green diesel production in the LFMM at the same level of detail as the other refining processes. However, this situation is likely to improve as commercial experience accumulates, and EIA should periodically contact the technology developers and monitor the technical literature in order to acquire technical and economic data on commercial green diesel production as such data become available.

Product Slate Flexibility

The LFMM should be implemented so that it is relatively straightforward to add either a new refinery process or a new renewable fuel pathway.

Petroleum Product Categories

Refinery-Produced Products

The LFMM will represent product categories similar to those in the PMM, as seen in **Figure 5.9**. The only difference is in motor gasoline and petrochemical feedstock. The non-oxygenated conventional gasoline will be eliminated in the LFMM because under the Renewable Fuel Standard, all gasoline will essentially be oxygenated (not mandated, but the level of RFS requirement will dictate its use in all gasoline). Petrochemical feedstock specific representations of propylene and aromatics will be added in the LFMM. Refineries are a major source of propylene and as refining operations adapt to changing petroleum product markets, there should be specific representation of propylene production.

Aromatics are high octane products whose alternate disposition is gasoline. Specific representation of these in the model will capture their impact on the gasoline octane balance. Allocation of propylene and aromatics within the petrochemical category will be based on historic and projection product portions.

Refinery Representation

Refinery Aggregation

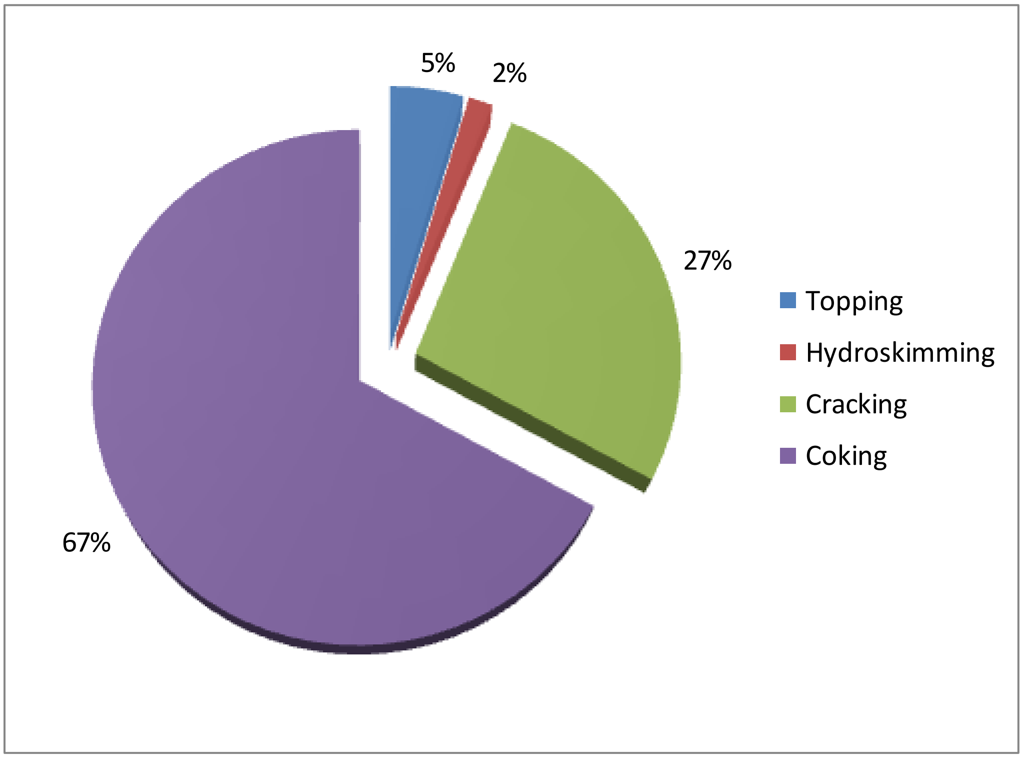
The LFMM will have the flexibility to model multiple refinery-type representations per refinery region. These refinery types will be an aggregation of the actual existing refineries in each region grouped into types by processing complexity. Four general refinery types are described in the literature[13]

- Topping: ACU only, produces naphtha but no gasoline
- Hydroskimming: Topping with naphtha reforming and treating processes
- Cracking: Hydroskimming with vacuum distillation and catalytic cracking

[13] "Crude Oil & Oil Sands Market Outlook 2010", Purvin & Gertz, Inc., 2010.

- Coking: Cracking with coking processes

Figure 5.21: Percent U.S. Distillation Capacity by Refinery Category[14]



As can be seen in **Figure 5.21**, the vast majority of refineries in the U.S. are either cracking or coking refineries. The LFMM will initially aggregate U.S. refineries into the following three types:

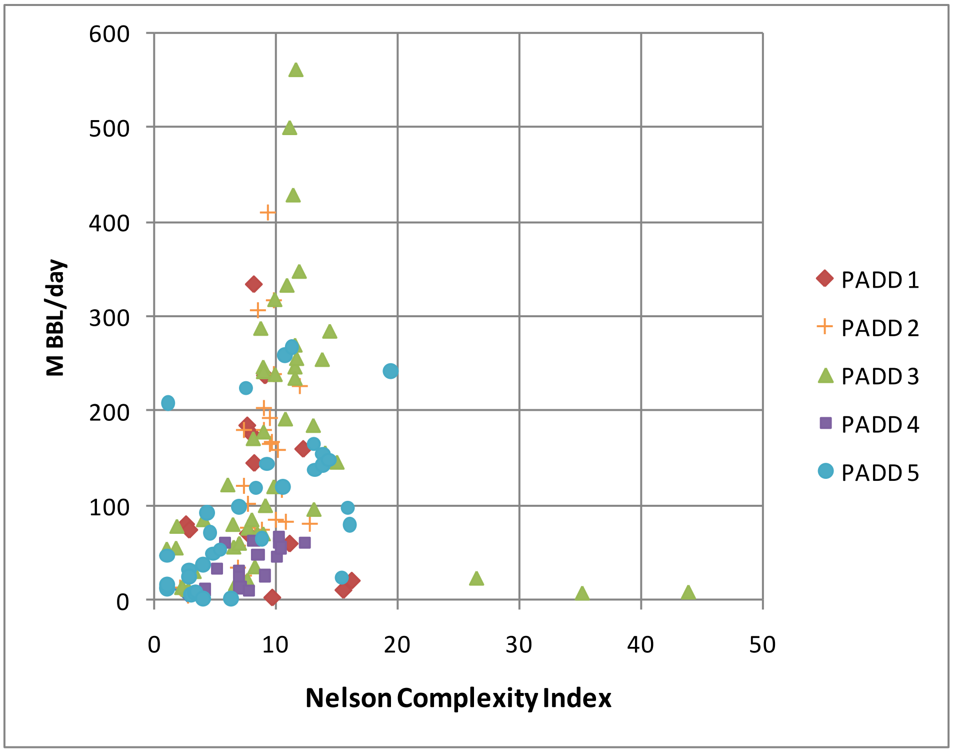
1. Topping and hydroskimming refineries
2. Cracking refineries
3. Coking refineries

Each of these refinery types will have different refinery economics and product yields for each slate of input crude processed, which should allow for a more robust representation of actual market conditions. Each refinery type will be allowed to add or retire capacity subject to the goal of delivering the demanded product slate at the lowest possible cost subject to available crude supplies of each crude type and varying crude price differentials.

The refinery groupings will be based on a variant of the Nelson Complexity Index[15] (NCI) score for each domestic refinery. The actual NCI values for domestic refineries can be seen in **Figure 5.22**.

[14] Data from (1) "The Need for Rationalization of Refining Capacity", Purvin & Gertz, Inc., July 2009 and (2) "2009 Worldwide Refining Survey", Oil and Gas Journal, December 21, 2009.

Figure 5.22: Complexity versus Capacity by PADD for U.S. Refineries



It is necessary to use a variant of the NCI score for the purposes of the LFMM because of the very-high-complexity low-capacity outliers in PADD 3, as seen in **Figure 5.22**. These are actually topping or hydroskimming refineries that have a high complexity score because they have some very expensive specialized capacity (e.g. lubricant production), but are really relatively simple refineries overall in terms of crude processing ability. As such, it would be inappropriate to group these into the cracking or coking refinery categories.

The separation of refinery representations will reduce the potential for over-optimization between complex and simple refinery types. It will also provide some indication of which refinery types are likely to survive as market conditions change over time.

During the prototyping phase of the LFMM, the number of refinery types may change if it is determined that a greater or lesser number of groupings yields a better trade-off between computing time and solution quality.

[15] "Worldwide Refinery and Complexity Analysis", Oil & Gas Journal Online Research Center, Daniel Johnston & Co., Inc., January 2010.

Ability to Address Natural Gas Liquids

Natural gas processing will not be included in the LFMM. The input to the LFMM will consist of natural gas for feedstock or fuel and other natural gas processing products for refinery processing or blending. The natural gas liquids produced as a byproduct of petroleum refining (LPG) will have a marginal price of production from the LFMM, but this price will have to be reconciled in some way with price of NGLs produced from natural gas extraction, a price that is generated in the NEMS Oil & Gas Supply Module.

Energy and Emissions Accounting Framework

U.S. Refinery Energy Use

Data reported by EIA [11] indicate that energy consumption in the U.S. refining sector is about three quads per year – about 3 percent of total U.S. energy consumption – and amounts to about 0.56 MMBTU/Bbl of refinery charge. U.S. refinery energy consumption, both total and per barrel of crude throughput, has tended to increase slowly over time. This trend reflects (1) U.S. refiners' gradual shift to a heavier, higher sulfur crude slate and (2) increasingly stringent specifications on refined products, particularly the sulfur standards for gasoline and diesel fuel. Per-barrel energy use by California refineries is higher than in the rest of the U.S. refining sector, because of the heavy crude slate run by California refineries and because of California's refined product specifications, the most stringent in the United States.

Data reported in EIA "Petroleum Supply Annuals" 2005, 2006, 2007, 2008 [15] show that the energy consumed in refining comes from numerous sources, some outside the refinery and some within. However, four sources – purchased natural gas and electricity, and refinery-produced still gas and catalyst coke – account for about 95 percent of reported U.S. refinery energy consumption.

- *Still gas* is a mixture of light gases (methane, ethane, etc.) produced as by-products in various refining processes. These light gas streams are collected, treated, and burned in the refinery fuel system to generate process heat and steam.

- *Catalyst coke* – coke laid down on FCC catalyst – is a by-product of the cracking reactions that occur in the FCC reactor. The coke is burned off the catalyst in the FCC regenerator. The heat of the combustion is then used to provide process energy for the FCC reactor and to generate refinery steam.[16]

EIA reports only refinery purchases of electricity that come from the grid; these reports do not include refinery-generated electricity, which largely comes from gas-fired cogeneration units. Gross power generation in U.S. refineries averaged about 2.6 gigawatts (63 gigawatt-hours per

[16] *Petroleum coke* (or *marketable coke*) – which is not used as a refinery fuel – is the primary by-product of refinery coking units (cokers). Petroleum coke constitutes ≈ 25–35 percent by weight of coker output and has various non-energy uses outside the refining industry.

day) in 2006. U.S. refineries sold about 29 percent of their gross power output to the grid, leaving about 1.9 gigawatts of indicated net power generation for internal use.[17]

Refinery purchases of natural gas reported by EIA appear to include natural gas used for all refinery power generation, without adjustment for refinery sales of electricity to the grid, but not natural gas used as either feed or fuel in merchant hydrogen plants.

Conceptual Framework for Estimating Refinery Energy Use

In principle, one can envision several approaches for estimating refinery energy use and CO_2 emissions.

The most rigorous approach is to develop complete energy, material, and carbon balances around the refinery. The difference between the energy embodied in all refinery outputs and inputs equals the energy expended in the refinery. Similarly, the difference between the total carbon content of all refinery outputs and inputs equals the refinery's carbon emissions. At first glance, this approach seems appealing because it rests on fundamental engineering principles of heat and material balance. In practice, the approach is unworkable. It requires the representation of complete material and energy balances for the refinery (including not only all refinery feed and product streams but also waste streams and losses, such as flue gas, flare gas, fugitive emissions, waste water, etc.) and precise estimates of the energy and carbon content of each refinery input and output. Such properties vary with crude type, are subject to day-to-day fluctuation, and in many cases are simply unavailable. Moreover, because the desired results – refinery energy use and CO_2 emissions – are residuals, the inevitable gaps in refinery material and energy balances and the inaccuracies in energy and carbon content would render such estimates useless.

The most useful approach focuses exclusively on energy consumption within the refinery "battery limits". This approach involves estimating energy use in each refining process and then estimating total refinery energy use as the sum of the energy used in each process – that is, by summing the direct energy inputs to all refining processes, by energy source (power, steam, and fuel). This is the approach of choice in industry LP models of refining operations and the one that will be followed in the LFMM.

Refinery Energy Accounting in the LFMM

Each process representation in the refining portion of the LFMM will include input/output coefficients representing the process's net per-barrel consumption of fuel (foeb/Bbl), steam K lbs/Bbl), and power (Kwh/Bbl). For any given process, the values of the fuel, steam, and power coefficients depend on the process operating conditions (e.g., severity, conversion, etc.) and feed streams.

In addition, the refining portion of the LFMM will contain representations of three refinery utilities:

[17]These estimates are derived from data reported by EIA in [12], [13], and [14].

- Fuel mixing that transforms candidate refinery fuel streams – natural gas, still gas, C3s, C4s, and light straight naphtha – into refinery fuel available to the various processes
- Steam generation that transforms catalyst coke and refinery fuel into steam available to the processes
- Power generation that transforms natural gas into power and steam

Finally, the LFMM will contain (1) constraints that equate net fuel, steam, and power consumption across all processes to the total refinery supplies of these energy forms and (2) accounting variables that sum the total volumes of the following power sources:

- Purchased natural gas, for use as refinery fuel (and as feed to hydrogen production)
- Refinery-generated still gas and other fuel gas streams
- Catalyst coke generated in the fluid catalytic cracking (FCC) unit
- Purchased electricity (net of sales)

The constraints span Sections 1 and 3 of the block diagram (**Figure 6.4** and **Figure 6.6**); the accounting variables are in Section 1 of the block diagram, column strip **Refinery Energy Use**.

Although some on-purpose hydrogen used by refineries is produced by merchant hydrogen plants, the LFMM will represent all such hydrogen as a product that is produced in the refinery.[18] Hence, refinery energy use in the model will include natural gas used as fuel in the production of hydrogen purchased from merchant plants (located outside the refinery battery limits).

The refinery energy accounting in the LFMM will not cover (1) energy used in production and transport of ethanol or other alternative fuels produced outside of refinery battery limits, whether blended to petroleum products at the refinery or downstream; (2) energy used in production and supply of purchased unfinished oils and blendstocks blended into gasoline and distillate fuels in the refinery, but not otherwise processed in the refinery; (3) power used in non-process or off-site activities (such as oil movements in and out of storage, product blending, lighting, etc.); and (4) energy losses due to flaring, fugitive emissions, etc.

Comparison with EIA Framework for Reporting U.S. Refinery Energy Use

All else being equal, the energy accounting framework described here should tend to produce estimates of regional refinery energy use somewhat lower (by $\approx$ 10 –12 percent) than the values reported by EIA. There are several reasons for this. First, the LFMM will not explicitly represent some auxiliary refinery process units (such as certain distillation and other separation processes), whose operations consume some energy. Second, the LFMM will not capture refinery energy use in non-process or off-site activities (e.g., oil movements in and out of crude and product tankage.) Third, the LFMM representation of energy use in the individual refining processes will

[18] Merchant hydrogen plants are not in the refinery proper, but the energy they use and the CO_2 they generate in producing hydrogen for refinery use are directly connected with refinery operations. In effect, the LFMM treats purchased hydrogen as though the merchant hydrogen plants were integral parts of the refining sector.

depend on reliable energy use coefficients for the various processes, especially those that are the primary energy consumers and producers. These coefficients should be based on information from technology providers (i.e., process developers and licensors).[19] Vendor-supplied information is usually the best to be had. However, it usually reflects best-practice operation of new process units at design conditions, and therefore probably understates actual energy consumption of the existing refinery capital stock in day-to-day refining operations.

In addition, the LFMM energy accounting framework will differ in a few respects from that used by EIA in reporting regional refinery energy use, especially with respect to natural gas and power purchases. As discussed above, refinery purchases of natural gas reported by EIA appear to include natural gas used for all refinery power generation, without adjustment for refinery sales of electricity to the grid, but not natural gas used as either feed or fuel in merchant hydrogen plants or as feed in refinery-based hydrogen plants.
Consequently, the LFMM energy accounting framework should be calibrated to regional energy use reported by EIA in a recent year, say 2008. Differences between the natural gas, purchased power, still gas, and catalyst volumes returned by the LFMM and those reported by EIA can be largely resolved either by adjusting energy use coefficients in certain process representations or by placing suitable adjustment factors on the energy accounting transfer variables.

Refinery CO_2 Emissions Accounting

The LFMM will use standard CO_2 emissions factors, which are shown in **Figure 5.23**, to convert computed volumes of purchased natural gas, refinery fuel gas streams, FCC catalyst coke, and purchased power, captured by the corresponding accounting variables, to refinery emissions of CO_2.

The CO_2 emission coefficients are in the matrix row strip **CO_2 Output** (**Figure 6.6**) on the column strips denoting FCC operations (where catalyst coke is burned) and refinery fuel operations (where refinery still gas and purchased natural gas are burned).

It is worth noting that the estimates of refinery CO_2 generation returned by the LFMM will reflect not only fuel consumption in all refining processes, but also the natural gas used as feed for all on-purpose hydrogen production.

[19]Information sourced by technology providers (i.e., process developers and licensors) can be obtained from articles in journals and trade publications, papers presented at meeting, or private communications.

Figure 5.23: CO2 Emission Factors

Refinery Energy Source	CO_2 Emission Factor (Me Tons/MM BTU)
Natural gas	0.0531
Still gas	0.0642
Petroleum coke	0.1020
Electricity (purchased)	0.0000
Electricity (refinery-generated)	0.0531

Note:
Purchased electricity factor reflects 50%/30%/20% sourcing from coal, natural gas, and nuclear + renewables, respectively.

Alternative Fuels CO_2 Emissions Accounting

The LFMM will use the accounting framework and standard CO_2 emissions factors discussed above to represent energy use and CO_2 emissions in the production of renewable fuels and other alternative fuels. The CO_2 emission coefficients are in the matrix row strip **CO_2 Output** (**Figure 6.6**).

Extension to CO_2 Emissions in Crude Oil Production and Transport

The approach for refinery CO_2 accounting delineated here can be extended to cover the CO_2 emissions associated with the production of crude oil and its transport to the refinery. This extension would require exogenous estimates of the average CO_2 emissions per barrel of crude oil for each crude oil type. These emissions will be represented in the LFMM as additional coefficients on the crude oil purchase variables at their intersection with the refinery accounting constraint **CO_2 Emissions** (**Figure 6.4**).

Extension to Other Refinery Emissions

The approach for refinery CO_2 accounting delineated here can be extended to other refinery emissions, such as SOx, NOx, and particulates. For each additional emission, the extension would involve adding to the block diagram one row strip analogous to **CO_2 Output**, one column strip analogous to column strip **CO_2 Emissions**, and a block of coefficients on the row strip to represent the appropriate emission factors.

Implementing this approach in the LFMM would require emissions factors for each emission of interest, analogous to the CO_2 emission factors shown in **Figure 5.23**. However, unlike CO_2, refinery emissions of SOx, NOx, and particulates can be affected significantly by control measures. Consequently, for these emissions, standard factors analogous to those shown in **Figure 5.23** are not easily estimated.

Carbon Capture and Storage

Carbon capture and storage (CCS) will be handled in the LFMM in accordance with the forthcoming approach being developed for the overall NEMS framework.

Treatment of Capital Stock Vintaging

In general, new installed capacity will have different operational parameters (variable cost, conversion efficiency, etc.) than capacity installed in prior years. To account for this, the proposed LFMM will keep track of running weighted averages of operating parameters for each refinery process, based on the amount of capacity installed in each model year.

Approach to Product Pricing

Shadow Prices, Markups, and Margins of Liquid Fuel Production

A key element of the model's solution will be the set of marginal prices on finished liquid fuels and petroleum products in each refining and alternative fuels region and in each end use region. Marginal prices of refined products in the refining regions will be given by the shadow prices on the constraints denoted by the set of matrix row strips under the heading **Refinery Out-turns** in the larger grouping **Refinery Input/Output Balances**. Marginal prices of alternative fuels produced in the alternative fuels regions will be given by the shadow prices on the constraints denoted by the set of matrix row strips **Alternative Fuels Product Balances**. Marginal prices in the end-use regions will be given by the shadow prices on the constraints denoted by the set of matrix row strips under the heading **Product Demand Balances**.

The marginal price of a liquid fuel or petroleum product in an end-use region is the sum of:

- The marginal cost of supply, computed in LFMM and comprising:
  - The marginal cost of production (in a refinery or alternative fuels plant) (1)
  - Transportation cost from production site to terminal (2)

- Per-gallon costs incurred in distribution to the end use region, added in post-solution processing and comprising:
  - Distribution costs and mark-ups from terminal to end-use point (3)
  - Federal and State taxes (4)
  - Cost of compliance with environmental policies such as RFS2 or LCFS (5)

Element (1) will be the endogenously computed shadow price of the given liquid fuel or petroleum product in the given production region. Element (2) will be an exogenously specified cost for the given product/production region/end-use region/mode combination. It appears on the appropriate transport activities at the intersection of the matrix column strip **Transport Refined: Products and Alternative Fuels** and the row strip **Accounting Balances: Transport Costs**. This cost will be transferred to the LFMM objective function.

Elements (3) and (4) will be exogenously specified costs for the given product/end-use region combination. Element (5) is likely to be a combination of margin values on the policy constraints and post-processing as in the PMM. For example, the total cost of complying with RFS2 will be distributed across all finished retail petroleum product prices. These costs will be added to the other two elements in post-solution processing.

Renewable Fuel and Carbon Policy Approaches

Representation of Policies That Put a Price on CO_2 Emissions

Certain national policies that might be imposed in the future – such as a direct national carbon tax or a national cap-and-trade regime governing carbon emissions – would impose an additional operating cost on U.S. refineries based on their refinery emissions of CO_2.

The imposed cost of CO_2 emissions, whether in the form of a tax or the market price of an emissions permit, could be incorporated in the LFMM by placing suitable objective function coefficients (denominated in $/ton of CO_2 emissions) on the refinery CO_2 accounting variables. These variables are in column strip **CO_2 Emissions** in Section 1 of the matrix block diagram (**Figure 6.4**).

Representation of a Low Carbon Fuels Standard

Low carbon fuels standards (LCFS) seek to limit the average lifecycle GHG emissions of the transportation fuels pool in future years to some value that is less than those emissions in a baseline year (e.g., 2005).

An LCFS representation could be incorporated in the LFMM by:

- Expanding the set of blending properties for each transportation fuels blendstock (refinery-produced or alternative fuel) to include a value denoting estimated lifecycle GHG emissions relative to the average of such emissions in the baseline year.

- Adding a row strip to the model statement that (1) takes the volume-weighted average of lifecycle GHG emissions across all transportation fuels pools and (2) constrains these averages to be less than or equal to the specified LCFS standard for the given year.

If the contemplated LCFS encompasses not only liquid fuels but also electricity used in electric vehicles, the LCFS constraint in the LFMM could be given credit for light-duty vehicle (LDV) electricity use (although it would have no direct influence on the propensity of consumers to buy electric vehicles.)

RFS2 Compliance and E85 Economics

Overview of the Renewable Fuels Representation in LFMM

The LFMM will represent renewable fuels supplies and dispositions as follows:

- Renewable fuels supplies (domestic and imported) will be represented by variables corresponding to production pathways (**Figure 5.13**), in the set of column strips **Produce Renewable Fuels** (domestic), and by exogenous supply functions in the set of column strips **Import Biofuels Blendstocks** (imported).

- Price steps in the supply functions for imports will be net of applicable subsidies and credits.

- The produced or imported biofuels will be labeled by RFS2 mandate category:
    - Renewable fuel
    - Advanced biofuel
    - Cellulosic ethanol
    - Biomass diesel

- The ethanol and biodiesel volumes will be summed by RFS2 mandate category (in the row strip **Special Constraints**); the volumes need not be constrained to meet the RFS2 schedule of annual mandate volumes (though they may be so constrained in the NEMS module representing bio-fuels production).

- All gasoline is recipe-blended in the end-use region to an ethanol content that is the lesser of (1) the maximum ethanol content allowed under prevailing Federal regulations (currently 10 percent by volume) or (2) the ethanol content that will absorb all the ethanol supplied.

- Ethanol supplies in excess of the volume required for gasoline blending, as described above, will go to E85 production. (E85 is the only motor fuel presently certified that could absorb large volumes of ethanol in excess of the national E10 volume.)[20] E85 prices would be set appropriately relative to motor gasoline so as to stimulate the correct mix of flex-fuel vehicle (FFV) demand in the NEMS transportation model, with the added E85 subsidization costs spread out over all other petroleum products sold. This is analogous to the current approach to E85 pricing in the PMM.

- The volume of E85 production will be converted to its energy-equivalent value for the purpose of satisfying the specified combined regional demands for gasoline and E85.[21]

- Purchased bio-mass feedstocks for refinery-based green diesel production will be represented as refinery intermediate streams that serve as inputs to the refinery green diesel process.

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[20]E85 is the only motor fuel presently certified that could absorb large volumes of ethanol in excess of the national E10 volume.

[21]From a regulatory standpoint, E85 is not gasoline, but of course it can be substituted for gasoline in flexible-fuel vehicles (FFVs).

This representation of ethanol supplies and disposition assumes that the impending ethanol "blend wall" will be accommodated either by EPA's relaxing the current 10 percent by volume limit on ethanol blending or by increasing use of E85 to absorb surplus ethanol.

Comments on Ethanol Pricing Beyond the E10 Barrier

At present, the volume of E85 use is negligible for NEMS and LFMM purposes. However, if EPA does not progressively relax the limit on ethanol content as the RFS2 mandate volume increases, then the indicated volume of E85 could be significant (at least in the Midwest). Such a situation poses substantial regulatory and analytical issues – particularly with respect to the pricing of E85 (and hence of ethanol) needed to make it attractive to consumers.

In order for consumers to buy it, E85 must be discounted substantially relative to E10 at the pump. The discount must reflect the factors that determine E85's value to consumers.

- **Low energy density**: E85 exposes ethanol's low energy density; E10 does not. E85 has about 21 percent lower energy density than E10. Hence, the E85 price must be 21 percent lower than the E10 price at the pump simply to compensate consumers for E85's lower energy density.
- **Extra refueling**: Because of the energy density effect, FFVs have less range when fueled with E85 than with E10, necessitating extra refueling stops. EPA estimates the value of consumer's time lost to extra refueling to be about 4¢/gal of E85, leading to a corresponding discount at the pump.[22]
- **Consumer loyalty**: FFV owners would have the option of fueling with E10 or E85. Furthermore, only a small portion of all gasoline stations would have E85 pumps. Assuming that about one-quarter of gasoline stations in E85 market areas would have E85 pumps by 2022 and using an "optimistic" estimate of the FFV share of the vehicle fleet, EPA estimated that E85 would have to be discounted by an additional 26¢/gal in 2022 to induce the volume of E85 use needed to satisfy the RFS2 volume mandate. (The "consumer loyalty" discount would have to increase over time as higher volumes of E85 were introduced to the marketplace.)

The net result is that E85 would have to be priced at retail about one-third lower than E10 by 2022. Correspondingly, ethanol would have to be priced (after VEETC) at the terminal nearly one-half lower than CBOB, reflecting the effects of Federal and State gasoline taxes, distribution costs, and mark-ups downstream of the terminal.

A fourth factor could further reduce the price that ethanol could command at the terminal if E85 were in the marketplace. Service station operators likely would require higher margins on E85 than on E10 to compensate for the installation of new tanks and pumps dedicated to E85 and for possibly lower sales volumes than E10.

[22] This estimate appears in EPA's recent *Draft Regulatory Impact Analysis* (DRIA) for its 2009 RFS2 rule [15].The DRIA has an extensive discussion of the factors affecting E85's value and pricing.

What is important about this analysis is not specific numbers (because considerable uncertainty exists regarding the estimates and underlying assumptions of E85 pump installations and FFV numbers) but rather its finding that ethanol would have to be priced at the terminal *considerably lower* than CBOB once E85 enters the market. Positing plausible sets of market conditions for crude oil, corn ethanol, and cellulosic ethanol that would support such ethanol/CBOB price relationships is not easy. It is more likely that significant volumes of E85 will enter the market only if E85 receives additional subsidies (e.g., through cross-subsidization by E10 or other petroleum fuels). This approach is similar to the one taken in the PMM under the RFS2 rule.

At present, EPA’s RIN system is the only mechanism available for establishing realized prices at the terminal for ethanol – corn ethanol, advanced biofuel ethanol, and cellulosic ethanol – that would enable E85 use consistent with the RFS2 annual mandate volumes.

In a hypothetical case, one may suppose that the plant gate price of corn ethanol (after VEETC) were equal to the rack price of CBOB. The resulting terminal prices for fuel ethanol and pump prices for E85 would be far too high to support E85 use, leading to a shortage of RINs in the aggregate. This shortage would induce an increase in the value (or market price) of RINS, because obligated parties would attempt to acquire more of them for compliance purposes. The price of RINs would be driven up until the effective price of ethanol at the terminal – the (after-VEETC) delivered price of corn ethanol minus the market price of a “renewable fuel RIN” – was low enough to permit E85 to be priced low enough relative to E10 to generate adequate aggregate sales of E85. This process would cause the retail price of E10 to increase, to account for the increased cost of RINs needed for compliance purposes. The net effect would be cross-subsidization of E85 by E10.

The RIN system would tend to equalize the “effective” terminal prices of corn ethanol, advanced biofuel ethanol, and cellulosic ethanol via prices set in the marketplace for each class of RIN.

EPA appears to have designed the RIN system mainly as a compliance mechanism – not as the central mechanism for establishing “effective” market prices for the various types of biofuels that are consistent with RFS2 annual mandate volumes. Consequently, EIA should give careful consideration to how – or if – it wishes to represent the formation of end-use prices for ethanol in NEMS and the LFMM.

6. Solution Methodology

Modeling Approach for the LFMM

The LP provides the most appropriate option for incorporating the complex refining technology, the crude and refined product qualities, and the economic factors that will establish crude and petroleum product prices and margins. The refinery LP provides a wide range of flexibility for adapting to changing environments and technology developments. Refinery LP models are used extensively throughout the refining industry for supply and economic planning, investment, and other analysis, often to arrive at solutions similar in scope to the proposed LFMM output within NEMS.

The prospective use of a refinery LP model for the LFMM raises concerns, particularly as to the complexity of the refining module and the potential to over-optimize and produce implausible results. While these concerns are well founded, they can be adequately mitigated through careful model design. Understanding the drivers of the refining industry and refining economics is critical to model design. With the proper balance, a manageable LP model system can be implemented within the LFMM, one with the capability to adequately meet the price, supply, demand and other projection requirements of NEMS.

Although this CDR proposes the LP approach for the initial prototype of the LFMM, other approaches may be considered in the future.

Alternative Approaches

Alternatives to the LP model approach for analysis of the liquid fuels market and projection of product prices are limited. Within the category of LP modeling there are some alternatives, and within the framework of the PMM regional refinery LP approach there are also alternative modeling approaches.

An economic model approach based on a system of equations would generate supply, demand, and price relationships based historic market data and analysis. However for the level of product detail included in NEMS and the nature of technology and technology/product interactions, it is questionable that such an approach could adequately reflect market behavior. Economic models would also be seriously limited in their ability to capture major market and technology changes.

Spreadsheet simulation systems have also been used to model liquid fuel production and product pricing relationships. However, these systems offer little flexibility to incorporate change or new technologies without exogenous input and recalibration. The spreadsheet model is also limited in its economic representations. Spreadsheet models have been combined with LP solvers, with the spreadsheet providing technology representations and the LP utilized for final refined product blending. This approach improves economic analytic capabilities, but does not improve on flexibility. It also requires a high level of exogenous input.

A hybrid LP model approach would develop refinery LP-generated yield vectors for incorporation into the NEMS liquid fuel representation. The yield vectors would cover a full range of processing options, and would also include relevant economic relationships. The NEMS liquid fuels module would consist of simplified regional LPs, incorporating traditional NEMS input to PMM and yield vectors, and producing the required output to NEMS. The hybrid approach would require a greater level of exogenous input in establishing yield vectors. In addition, flexibility and integrity of refining representations would be compromised. And, although the NEMS liquid fuel relationship could be simplified, the level of complexity in the exogenous refinery LP/NEMS liquid fuels system may not provide any significant improvement in the level of complexity and transparency.

Within the refinery LP model approach there are two technology representation options which will lead to very different model structures. The current PMM employs a “table driven approach” to representing intermediate streams and qualities and downstream refinery process yields. Intermediates are characterized by combinations of “high” and “low” quality streams and process yields provided for each intermediate type. The advantage of this approach is that it allows for a less complex mathematical solver and one consistent with the current PMM. The disadvantage is that as model representations include greater numbers of processing options, the number of intermediate streams and processing options increases and the model becomes more complex. Furthermore, as the model expands, so do opportunities for selectively choosing intermediate and processing options beyond real world capability, resulting in model over-optimization. The over-optimization tendency with this approach can be minimized by simplifying and managing updates and expansions to technology representations, and by using policy pooling constraints. The latter will mitigate most major over-optimization issues, but requires additional exogenous input and introduces the possible risk of overly restrictive constraints.

The alternative to the PMM “table driven approach” uses a property driven component or recursion approach (referred to as recursion in the remainder of this CDR). Intermediate streams are pooled and properties calculated and tracked throughout the refinery processing. Process yields are specified as a base yield (per a specified feed quality) and delta yields which adjust for feed quality differences. The advantages of this approach include a less complex processing structure, reduced opportunity for over-optimization, greater transparency, and greater flexibility to add/modify technologies without expanding the process model or model complexity.

Table 6.1 summarizes advantages/shortcomings of the table driven and recursion approaches for the LFMM. In general, the recursion approach offers the potential for a simpler model process technology structure, a better platform for incorporating future processing additions or modifications, less opportunity for over-optimization, and potential for better representation of marginal aggregate refining operations and economics. On the other hand, converting to the recursion approach will likely require additional model development time as well as time for development of internal expertise for model formulation and operation. The recursion approach also raises concerns with model convergence issues.

Table 6.1: Comparison of Table-Driven Versus Recursion Approach

Table Driven Approach	Recursion Approach
1. Structure of model technology representations	
Requires tracking/representation of individual intermediate streams by quality	Model tracks/calculates intermediate stream qualities
Expansion of number and type of intermediate streams to accommodate new process technologies and operating modes	Processing representations developed based on a base yield vector and a delta vector. No need for expansion of individual intermediate streams
Increased opportunity for over-optimization (related to "cherry-picking) between high/low quality intermediates for processing	Downstream operations and yields based on pooled qualities. Little opportunity to selectively allocate (optimize) based on range of intermediate stream quality
2. Representation of marginal refinery operations and economics	
Marginal operations/economics may be driven by "extreme" high/low quality intermediates	Potential for better representation of marginal aggregate refining operations/economics
	Use of aggregate pooling reduces need for (value of) multiple refinery technology types represented in model.
3. Compatibility with existing technology representation	
Similar process technology structure	Revised representations and approach
Some representations can be retained	
Straight forward component quality representations and input	Revised component quality correlations (qualities function of processing) need to be developed
4. Model development issues	
Experience with table approach	Need to develop expertise in modeling approach
	Likely greater model development time and resources required
5. Model execution issues	
	Tendency for non-convergence. Would likely need to develop level of model experience to deal with convergence issues (additional model development time)

The table driven approach is more compatible with the existing PMM structure and personnel expertise, and may enable greater use of existing process data and correlations. Although technology representations can become complex due to expanding numbers of streams represented, individual vectors represented are straightforward and transparent. Convergence issues are far less of concern with the table driven approach.

Regardless of the modeling approach selected (LP or other), the scope and boundaries selected for the LFMM will have a large impact on model performance and complexity. In this regard, the LFMM will be severely disadvantaged without a reasonable representation of international crude and product market interfaces.

Specific Model Structure

The table-driven LP approach has been chosen for the initial LFMM development effort; although a recursion approach could be attempted in the future if deemed necessary.

Matrix Representation of Model Design

The preliminary Model Design is presented here in the form of an LP matrix schematic – as defined in an earlier section. The presentation is in a series of figures.

- **Figure 6.2** is a high level block diagram delineating the overall architecture of the LFMM. It shows the LFMM as comprising five large clusters of column strips, representing respectively:
    - Accounting variables (financial, energy use, CO_2 production) and variables that sum capacity investments, additions, and retirements
    - Input supply operations, including acquisition and delivery of crude oils, other refinery input streams, biomass and other alternative fuels feeds, and purchased energy
    - Refining operations, including refining process and utilities operations and refined product blending
    - Alternative fuels production operations, including renewable fuels, CTL, and BTL process
    - Product supply operations, including transport from refining regions to demand regions and local blending of certain finished products (e.g., E10 and E85)

- **Figure 6.3** is a stylized diagram that shows the block diagram divided into five named sections. Each section denotes a set of column strips that represents one of the large sectors of the model (e.g., Section 1 represents the accounting and capacity variables; Sections 3a and 3b represent refinery operations (process units and product blending, respectively)). This figure is a kind of road map to the five figures that follow.
- **Figure 6.4** through **Figure 6.8** as a group show the complete block diagram in full detail. Each figure shows a contiguous set of column strips that constitute one of the block diagram sections shown in **Figure 6.3**.[23]

[23]Dividing the block diagram into sections is inconvenient, no doubt to the reader and certainly to the author. However, it is unavoidable because the complete block diagram is too big to fit on one page and still be visible. To see the entire block diagram at once (which is highly recommended), one must lay out the five sections side by side and tape them together.

- **Figure 6.9** is the *column strip catalog*, listing all of the model's column strips, showing the attributes over which each column strip is defined, and briefly describing each column strip.
- **Figure 6.10** is the *row strip catalog*, listing all the model's row strips, showing the attributes over which each row strip is defined, and briefly describing each row strip.

The row and column strip attributes shown in **Figure 6.9** and **Figure 6.10** correspond to the list of attributes shown in **Figure 5.4**.

Figure 6.2: High Level LFMM Block Diagram

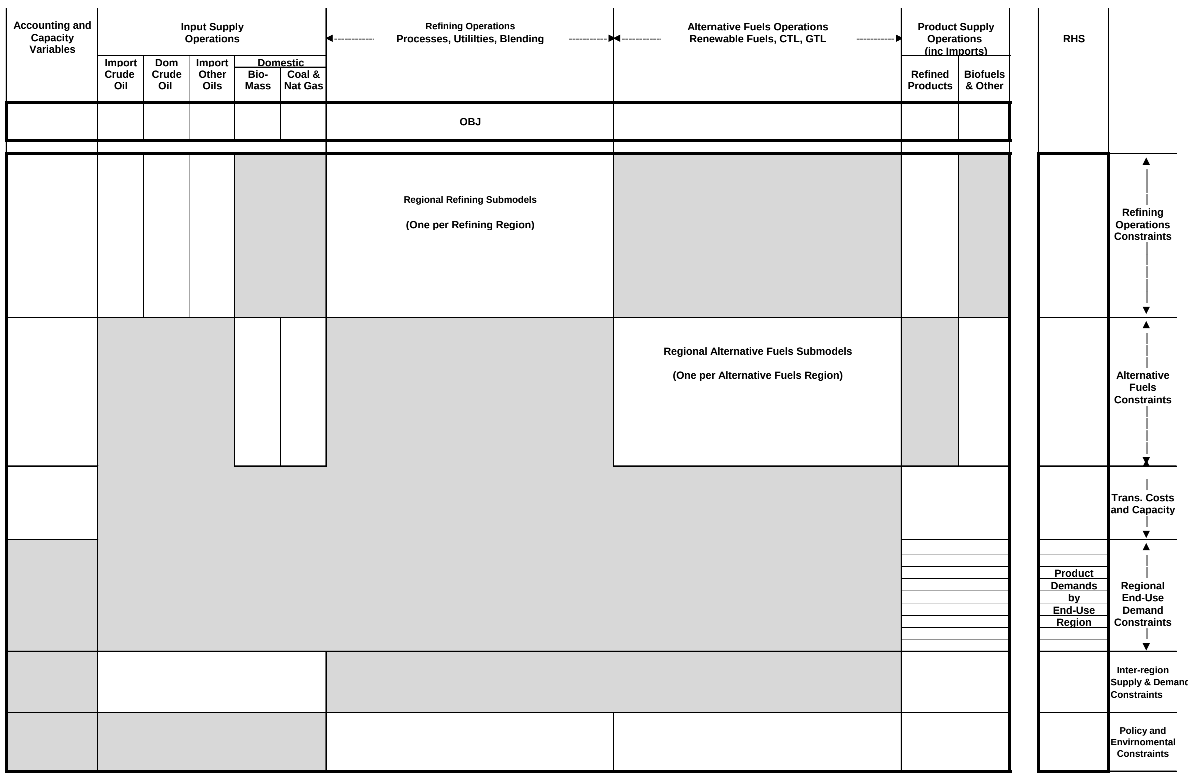

Figure 6.3: Column Section Roadmap of the Detailed LFMM Block Diagram

Accounting Relationships	Input Supply Operatons	Refining Operations:	Refining Operations	Alternative Fuels Operations	Product Supply Operations:		
Track Financial, Energy, and CO2 Flows Track Capacity Additions/Retirements	Purchase and Transport Crude Oil, Other Refinery Inputs Refinery Energy Sources	Operate Refiining Processes, and Utilities	Product Blending	Renewable Fuels, CTL, GTL	Product Import, Product Transport, Terminal Blending, Delivery	≤	RHS

Figure 6.4: Matrix Block Diagram - Section 1: Financial, Energy/CO2 and Capacity Accounting

		Refining Accounting			Alternative Fuels Accounting			Use/Add/Retire Refining Capacity					Use/Add/Retire Alt Fuels Capacity				Use/Add Transport Cap.		Row Type	RHS
		Cost Elements	Refinery Energy Use	CO2 Emissions	Cost Elements	Plant Energy Use	CO2 Emissions	Use Existing Capacity	Add New Capacity	Retrofit Capacity	Slack Capacity	Shut Down Capacity	Use Existing Capacity	Add New Capacity	Retrofit Capacity	Shut Down Capacity	Use Existing Capacity	Add New Capacity		
	Objective Function	-1 +1 +1 +1 +1		CO2_price	-1 +1 +1 +1		CO2_price												Free	
Accounting Balances	Revenues	+1			+1														=	0
	Input costs	-1			-1														=	0
	Variable op costs	-1	NRG_cost		-1	NRG_cost													=	0
	Transport costs	-1																	=	0
	Capital costs	-1			-1				NRC_capcost	RRC_capcost				NAC_capcost	RAC_capcost			NTC_capcost	=	0
Energy / CO2 Balances	Energy Use		-1			-1													=	0
	CO2 Output			-1			-1												=	0
Capacity Balances	Refining Capacity							-1	-NRC_sf	+1/-1	-1	+SRC_sf							=	0
	Refining Cap S/D							- SRC_rat			+1								≤	0
	Refining Investment								NRC_inv	RRC_inv									≤	INV_LIM
	Alt Fuels Capacity												-1	-NAC_sf	+1/-1	+SAC_sf			≤	0
	Alt Investment													NAC_inv	RAC_inv				≤	INV_LIM
	Transport Capacity																-ETC_sf	-NTC_sf	≤	0
	Transport Investment																	NTC_inv	≤	INV_LIM
Refinery Input Stream Limits	NGL																		≤	
	Crude Oil																		≤	
	Unfinished Oils																		≤	SUPPLY
	Blendstocks																		≤	
	Alternative Fuels																		≤	
Refinery Input Stream Balances	NGL																		≤	0
	Crude Oil																		≤	0
	Unfinished Oils																		≤	0
	Blendstocks																		≤	0
	Alternative Fuels																		≤	0
Refinery Input / Output Balances (Volumetric)	Refinery Inputs																			
	Crude oil																		≤	0
	NGL																		≤	0
	Intermediate Strms																		≤	0
	Refinery Out-turns																			
	Gasoline BOBs																		≤	0
	Jet																		≤	0
	Distillates																		≤	0
	Resids																		≤	0
	Petchem feeds																		≤	0
	All other products																		≤	0
Refinery Blending Volume Balances	Gasoline BOBs																		≤	0
	Jet																		≤	0
	Distillates																		≤	0
	Resids																		≤	0
Refinery Blending Specification Balances	Gasoline BOBs																		≤ , ≥	0
	Jet																		≤ , ≥	0
	Distillates																		≤ , ≥	0
	Resids																		≤ , ≥	0
Alt. Fuels Production Input Stream Balances	Corn starch																		≤	0
	Sugar cane																		≤	0
	Biomass solids																		≤	0
	Biomass liquids																		≤	0
	Coal																		≤	0
	Natual gas																		≤	0
Alt. Fuels Product Balances	Ethanol																		≤	0
	Butanol																		≤	0
	Diesel																		≤	0
	Other																		≤	0
	CTL																		≤	0
	GTL																		≤	0
Special Constraints	Δ Crude oil quality																		≤ , ≥	CR_LIM
	Technical (refining)																		≤ , ≥	0
	Technical (alt fuels)																		≤ , ≥	0
Terminal Blending Balances	Gasoline BOBs																		≤	0
	Distillates																		≤	0
	Ethanol																		≤	0
	Butanol																		≤	0
	Biodiesel																		<	0
Policy Constraints	Policy (enviro)																		≤ , ≥	E_POLICY
	Policy (refining)																		≤ , ≥	R_POLICY
	Policy (transport)		+1	+1		+1	+1												≤ , ≥	T_POLICY
Product Demand Balances	Gasoline / CenReg N																		≤	
	E85 / CenReg N																		≤	
	Jet / CenReg N																		≤	0
	Distillates / CenReg N																		≤	
	Resids / CenReg N																		≤	
	Petchem feeds																		≤	
	All other products																		≤	
Upper Bounds								ERC_ul	NRC_ul	RRC_ul		SRC_val	EAC_ul	NAC_ul	RAC_ul	SAC_val	ETC_ul			
Lower Bounds								ERC_ll				SRC_val				SAC_val				

Figure 6.5: Matrix Block Diagram - Section 2: Input Supply Operations

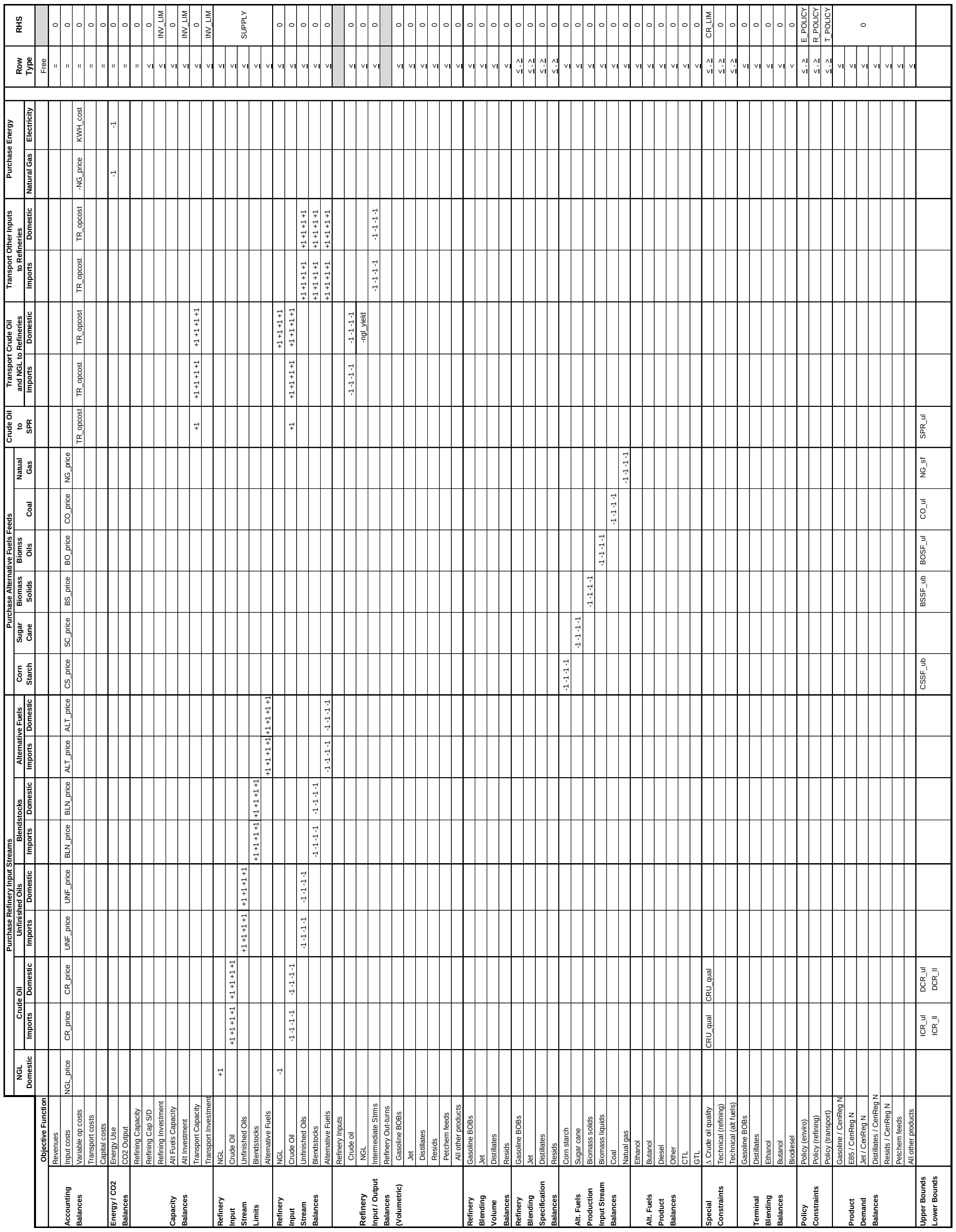

Figure 6.6: Matrix Block Diagram - Sections 3a and 3b: Refining Operations

		Operate CDUs		Operate Refining Processes						Operate Refinery Utilities			Transfer	Specification Blending								Recipe Blending			
														Allocate Blendstock Volumes to Products				Meet Product Specifications ("Spec Vectors")							
		Atmos.	Vacuum	Resid Upgrading	Cracking (current)	Gasoline Upgrading	Hydro-treating	Splitting / Fractionatn	Non-fuel Processes	Hydrogen Prod / Rec	CHP Generation	Refinery Fuel	Refinery Streams	Gaso BOBs	Jet	Distillates	Resid Fuels	Gaso BOBs	Jet	Distillates	Resid Fuels	Petchem Feedstks	All Other Products	Row Type	RHS
	Objective Function																							Free	
Accounting Balances	Revenues																							=	0
	Input costs																							=	0
	Variable op costs	var_cost	var_cost	var_cost	var_cost	var_cost	var_cost	var_cost	var_cost	var_cost	var_cost	var_cost	var_cost	var_cost	var_cost	var_cost	var_cost					var_cost	var_cost	=	0
	Transport costs																							=	0
	Capital costs																							=	0
Energy / CO2 Balances	Energy Use	nrg_use	nrg_use	nrg_use	-nrg_use	nrg_use	nrg_use	nrg_use	nrg_use	nrg_use	-nrg_prod	-nrg_prod		nrg_use	nrg_use	nrg_use	nrg_use					nrg_use	nrg_use	=	0
	CO2 Output				-CO2_fac					-CO2_fac	-CO2_fac	-CO2_fac												=	0
Capacity Balances	Refining Capacity	+1	+1	cap_cons	cap_cons	cap_cons	cap_cons	cap_cons	cap_cons	+1	+1													=	0
	Refining Cap S/D																							≤	0
	Refining Investment																							≤	INV_LIM
	Alt Fuels Capacity																							≤	0
	Alt Investment																							≤	INV_LIM
	Transport Capacity																							≤	0
	Transport Investment																							≤	INV_LIM
Refinery Input Stream Limits	NGL																							≤	
	Crude Oil																							≤	
	Unfinished Oils																							≤	SUPPLY
	Blendstocks																							≤	
	Alternative Fuels																							≤	
Refinery Input Stream Balances	NGL																							≤	0
	Crude Oil																							≤	0
	Unfinished Oils																							≤	0
	Blendstocks																							≤	0
	Alternative Fuels																							≤	0
Refinery Input / Output Balances (Volumetric)	Refinery Inputs																								
	Crude oil	+1	vac_res																					≤	0
	NGL																							≤	0
	Intermediate Strms	-cdu_yield	-cdu_yield	inp/out (+/-)	inp/out (+/-)	inp/out (+/-)	inp/out (+/-)	inp/out (+/-)	inp/out (+/-)	inp/out (+/-)	+ input	+ input	inp/out (+/-)	+1	+1	+1	+1					+1	+1	≤	0
	Refinery Out-turns																								
	Gasoline BOBs																	-1						≤	0
	Jet																		-1					≤	0
	Distillates																			-1				≤	0
	Resids																				-1			≤	0
	Petchem feeds																					-1		≤	0
	All other products																						-1	≤	0
Refinery Blending Volume Balances	Gasoline BOBs													-1				+1						≤	0
	Jet														-1				+1					≤	0
	Distillates															-1				+1				≤	0
	Resids																-1				+1			≤	0
Refinery Blending Specification Balances	Gasoline BOBs													qual_gas				-Spec-gas						≤ , ≥	0
	Jet														qual_gas				-Spec_E85					≤ , ≥	0
	Distillates															qual_dist				-Spec_dist				≤ , ≥	0
	Resids																qual_resd				-Spec_resd			≤ , ≥	0
Alt. Fuels Production Input Stream Balances	Corn starch																							≤	0
	Sugar cane																							≤	0
	Biomass solids																							≤	0
	Biomass liquids																							≤	0
	Coal																							≤	0
	Natual gas																							≤	0
Alt. Fuels Product Balances	Ethanol																							≤	0
	Butanol																							≤	0
	Diesel																							≤	0
	Other																							≤	0
	CTL																							≤	0
	GTL																							≤	0
Special Constraints	Δ Crude oil quality																							≤ , ≥	CR_LIM
	Technical (refining)			process feed constraints, operations constraints, etc.																				≤ , ≥	0
	Technical (alt fuels)																							≤ , ≥	0
Terminal Blending Balances	Gasoline BOBs																							≤	0
	Distillates																							≤	0
	Ethanol																							≤	0
	Butanol																							≤	0
	Biodiesel																							<	0
Policy Constraints	Policy (enviro)																							≤ , ≥	E_POLICY
	Policy (refining)																							≤ , ≥	R_POLICY
	Policy (transport)																							≤ , ≥	T_POLICY
Product Demand Balances	Gasoline / CenReg N																							≤	
	E85 / CenReg N																							≤	
	Jet / CenReg N																							≤	0
	Distillates / CenReg N																							≤	
	Resids / CenReg N																							≤	
	Petchem feeds																							≤	
	All other products																							≤	
Upper Bounds Lower Bounds													Tran_ul												

Figure 6.7: Matrix Block Diagram - Section 4: Alternative Fuels Accounting

		Produce Renewable Fuels							Produce Alt Fuels		Import Biofuels Blendstocks		Meet RFS2 Mandates	Row Type	RHS
		Ethanol (corn)	Ethanol (sugar)	Ethanol (cellulos)	Butanol (corn)	Diesel (biomas)	Diesel (cellulos)	Other	CTL	GTL	Ethanol	Biodiesl			
	Objective Function													Free	
Accounting Balances	Revenues	bypr_rev			bypr_rev				bypr_rev	bypr_rev				=	0
	Input costs										Et_Price	Et_price		=	0
	Variable op costs	var_cost	var_cost	var_cost	var_cost	var_cost	var_cost	var_cost	var_cost	var_cost				=	0
	Transport costs													=	0
	Capital costs													=	0
Energy / CO2 Balances	Energy Use	nrg_use	nrg_use	nrg_use	nrg_use	nrg_use	nrg_use	nrg_use	nrg_use	nrg_use				=	0
	CO2 Output													=	0
Capacity Balances	Refining Capacity													=	0
	Refining Cap S/D													≤	0
	Refining Investment													≤	INV_LIM
	Alt Fuels Capacity	cap_cons	cap_cons	cap_cons	cap_cons	cap_cons	cap_cons	cap_cons	cap_cons	cap_cons				≤	0
	Alt Investment													≤	INV_LIM
	Transport Capacity													≤	0
	Transport Investment													≤	INV_LIM
Refinery Input Stream Limits	NGL													≤	
	Crude Oil													≤	
	Unfinished Oils													≤	SUPPLY
	Blendstocks													≤	
	Alternative Fuels													≤	
Refinery Input Stream Balances	NGL													≤	0
	Crude Oil													≤	0
	Unfinished Oils													≤	0
	Blendstocks													≤	0
	Alternative Fuels													≤	0
Refinery Input / Output Balances (Volumetric)	Refinery Inputs														
	Crude oil													≤	0
	NGL													≤	0
	Intermediate Strms													≤	0
	Refinery Out-turns														
	Gasoline BOBs													≤	0
	Jet													≤	0
	Distillates													≤	0
	Resids													≤	0
	Petchem feeds													≤	0
	All other products													≤	0
Refinery Blending Volume Balances	Gasoline BOBs													≤	0
	Jet													≤	0
	Distillates													≤	0
	Resids													≤	0
Refinery Blending Specification Balances	Gasoline BOBs													≤ , ≥	0
	Jet													≤ , ≥	0
	Distillates													≤ , ≥	0
	Resids													≤ , ≥	0
Alt. Fuels Production Input Stream Balances	Corn starch	+1			+1									≤	0
	Sugar cane		+1											≤	0
	Biomass solids			+1			+1							≤	0
	Biomass liquids					+1								≤	0
	Coal								+1					≤	0
	Natural gas									+1				≤	0
Alt. Fuels Product Balances	Ethanol	-yld	-yld	-yld										≤	0
	Butanol				-yld									≤	0
	Diesel					-yld	-yld							≤	0
	Other	-yld			-yld			-yld						≤	0
	CTL								-yld					≤	0
	GTL									-yld				≤	0
Special Constraints	Δ Crude oil quality													≤ , ≥	CR_LIM
	Technical (refining)													≤ , ≥	0
	Technical (alt fuels)													≤ , ≥	0
Terminal Blending Balances	Gasoline BOBs													≤	0
	Distillates													≤	0
	Ethanol										-1			≤	0
	Butanol													≤	0
	Biodiesel											-1		<	0
Policy Constraints	Policy (enviro)										+1			≤ , ≥	E_POLICY
	Policy (refining)													≤ , ≥	R_POLICY
	Policy (transport)													≤ , ≥	T_POLICY
Product Demand Balances	Gasoline / CenReg N													≤	
	E85 / CenReg N													≤	
	Jet / CenReg N													≤	0
	Distillates / CenReg N													≤	
	Resids / CenReg N													≤	
	Petchem feeds													≤	
	All other products													≤	
Upper Bounds															
Lower Bounds													VM_II		

Figure 6.8: Matrix Block Diagram - Section 5: Product Supply Operations

		Import Finished Products			Transport Refined Products and Alternative Fuels to Demand Regions											Recipe Blend at Terminal			Supply Finished Products			
		Gasoline BOBs	Diesel	All Others	Gasoline BOBs	Jet Fuel	Distillates	Resids	Pet Chem Feedstock	All Other Products	Ethanol	Butanol	Biodiesel	CTL	CTL	Gasoline	E85	Biodieel	Exports	Domestic	Row Type	RHS
	Objective Function																				Free	
Accounting Balances	Revenues																		-price		=	0
	Input costs	IG_price	ID_price	IP_price																	=	0
	Variable op costs																				=	0
	Transport costs				tr_cost	tr_cost	tr_cost	tr_cost	tr_cost	tr_cost	tr_cost	tr_cost	tr_cost	tr_cost	tr_cost						=	0
	Capital costs																				=	0
Energy / CO2 Balances	Energy Use																				=	0
	CO2 Output																				=	0
Capacity Balances	Refining Capacity																				=	0
	Refining Cap S/D																				≤	0
	Refining Investment																				≤	INV_LIM
	Alt Fuels Capacity																				≤	0
	Alt Investment																				≤	INV_LIM
	Transport Capacity	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1				+1 +1 +1 +1 +1		≤	0
	Transport Investment																				≤	INV_LIM
Refinery Input Stream Limits	NGL																				≤	
	Crude Oil																				≤	
	Unfinished Oils																				≤	SUPPLY
	Blendstocks																				≤	
	Alternative Fuels																				≤	
Refinery Input Stream Balances	NGL																				≤	0
	Crude Oil																				≤	0
	Unfinished Oils																				≤	0
	Blendstocks																				≤	0
	Alternative Fuels																				≤	0
Refinery Input / Output Balances (Volumetric)	Refinery Inputs																					
	Crude oil																				≤	0
	NGL																				≤	0
	Intermediate Strms											+1		+1	+1						≤	0
	Refinery Out-turns																					
	Gasoline BOBs				+1														+1		≤	0
	Jet					+1													+1		≤	0
	Distillates						+1												+1		≤	0
	Resids							+1											+1		≤	0
	Petchem feeds								+1										+1		≤	0
	All other products									+1									+1		≤	0
Refinery Blending Volume Balances	Gasoline BOBs																				≤	0
	Jet																				≤	0
	Distillates																				≤	0
	Resids																				≤	0
Refinery Blending Specification Balances	Gasoline BOBs																				≤ , ≥	0
	Jet																				≤ , ≥	0
	Distillates																				≤ , ≥	0
	Resids																				≤ , ≥	0
Alt. Fuels Production Input Stream Balances	Corn starch																				≤	0
	Sugar cane																				≤	0
	Biomass solids																				≤	0
	Biomass liquids																				≤	0
	Coal																				≤	0
	Natual gas																				≤	0
Alt. Fuels Product Balances	Ethanol										+1										≤	0
	Butanol											+1									≤	0
	Diesel												+1								≤	0
	Other																				≤	0
	CTL													+1							≤	0
	GTL														+1						≤	0
Special Constraints	∆ Crude oil quality																				≤ , ≥	CR_LIM
	Technical (refining)																				≤ , ≥	0
	Technical (alt fuels)																				≤ , ≥	0
Terminal Blending Balances	Gasoline BOBs	-1			-1											+ghcont	+85hcont				≤	0
	Distillates		-1				-1							-1	-1			+dhcont			≤	0
	Ethanol										-1					+gecont	+85econt				≤	0
	Butanol											-1				+ghcont	+85hcont				≤	0
	Biodiesel												-1					+drcont			<	0
Policy Constraints	Policy (enviro)																				≤ , ≥	E_POLICY
	Policy (refining)																				≤ , ≥	R_POLICY
	Policy (transport)																				≤ , ≥	T_POLICY
Product Demand Balances	Gasoline / CenReg N															-1				+1	≤	
	E85 / CenReg N																-1			+1	≤	
	Jet / CenReg N			-1		-1														+1	≤	0
	Distillates / CenReg N																	-1		+1	≤	
	Resids / CenReg N			-1				-1												+1	≤	
	Petchem feeds			-1					-1											+1	≤	
	All other products			-1						-1										+1	≤	
Upper Bounds Lower Bounds																			EXP_ul	DMD_ul = DMD_ll		

Figure 6.9: Column Strip (Variable) Catalog

Variable Classes		Attributes				Description
Refinery	Cost Elements	REF_REG	ACCNTG			Sums of revenues and costs, by accounting category
Accounting	Refinery Energy Use	REF_REG	NRG_REF			Sums of refinery energy use, by energy source
	CO2 Emissions	REF_REG	CO2_SRC			Sums of refinery CO2 emissions, by source
Alternative Fuels	Cost Elements	ALT_REG	ACCNTG			Sums of revenues and costs, by accounting category
Accounting	Plant Energy Use	ALT_REG	NRG_REF			Sums of process energy use, by energy source
	CO2 Emissions	ALT_REG	CO2_SRC			Sums of plant CO2 emissions, by source
	Use Existing Capacity	REF_REG	UNIT			Existing refining capacity used
Use/Add/Retire	Add New Capacity	REF_REG	UNIT			New refining capacity via additions and expansions
Refining Capacity	Retrofit Capacity	REF_REG	RET_FIT			New refining capacity via retrofitting existing units
	Shut Down Capacity	REF_REG	UNIT			Existing refinery capacity shut down
	Use Existing Capacity	ALT_REG	ALT_UNIT			Existing alternative fuels capacity used
Use/Add/Retire	Add New Capacity	ALT_REG	ALT_UNIT			New alternative fuels capacity via additions and expansions
Alt Fuels Capacity	Retrofit Capacity	ALT_REG	RET_FIT			New alternative fuels capacity via retrofitting existing units
	Shut Down Capacity	ALT_REG	ALT_UNIT			Existing production capacity shut down
Use/Add	Use Existing Capacity	REF_REG	DEM_REG	SOURCE	TR_MODE	Existing transport capacity utilized
Transp. Capacity	Add New Capacity	REF_REG	DEM_REG	SOURCE	TR_MODE	New transport capacity added
	NGL Domestic	REF_REG		PRICE		NGL purchase volume
	Crude Oil - Imports	REF_REG	CRUDE_I	PRICE		Crude oil volume - imported
	Crude Oil - Domestic	REF_REG	CRUDE_D	PRICE		Crude oil volume - domestic
Purchase	Unfinished Oils - Imports	REF_REG	UNF_OIL	PRICE		Unfinished oils volume - imported
Refinery Input	Unfinished Oils - Domestic	REF_REG	UNF_OIL	PRICE		Unfinished oils volume - domestic
Streams	Blendstocks - Imports	REF_REG	BLNSTK	PRICE		Blendstock volume - imported
	Blendstocks - Domestic	REF_REG	BLNSTK	PRICE		Blendstock volume - domestic
	Alt. Fuels - Imports	REF_REG	ALT_FUEL	PRICE		Alternative fuel volume - imported (CTL, GTL)
	Alt. Fuels - Domestic	REF_REG	ALT_FUEL	PRICE		Alternative fuel volume - domestic (CTL, GTL)
	Corn	ALT_REG	RFS_FEED	PRICE		Corn supply volume
Purchase	Biomass solids	ALT_REG	RFS_FEED	PRICE		Biomass solids volum
Alternative Fuels	Biomass oils	ALT_REG	RFS_FEED	PRICE		Biomass oils volume
Feeds	Coal	ALT_REG	HC_FEED	PRICE		Coal volume (for CTL production)
	Natural Gas	ALT_REG	HC_FEED	PRICE		Natural gas volume (for GTL production
Crude Oil to SPR		REF_REG	CRUDE			Crude oil volume sent to SPR
Transport Crude Oil	Imports	REF_REG	CRUDE_I		TR_MODE	Imported crude volume transported to refining region
and NGL to Refineries	Domestic	REGION	CRUDE_D	SOURCE	TR_MODE	Domestic crude volume transported to refining region
Transport Other	Imports	REF_REG	REF_INP			Volume transported of other refinery input - imported
Inputs to Refineries	Domestic	REGION	REF_INP	TR_MODE		Volume transported of other refinery input - domestic
Purchase	Natural Gas	REGION	NRG_PUR			Purchased natural gas volume
Energy	Electricity	REGION	NRG_PUR			Purchased electricity quantity
Operate	Atmospheric	REF_REG	CDU	CRUDE		Volume of crude oil processed in atmospheric crude unit
CDUs	Vacuum	REF_REG	CDU	CRUDE		Volume of crude oil processed in vacuum crude unit
	Resid Upgrading	REF_REG	UNIT	OP_MODE		Through-put volume: resid upgrading units
Operate	Cracking (current)	REF_REG	UNIT	OP_MODE		Through-put volume: FCC and hydrocracking units
Refining	Cracking (future)	REF_REG	UNIT	OP_MODE		Through-put volume: FCC and hydrocracking units (future tech)
Processes	Gasoline Upgrading	REF_REG	UNIT	OP_MODE		Through-put volume: alkylation, reforming, isom units, etc.
	Hydrotreating	REF_REG	UNIT	OP_MODE		Through-put volume: hydrotreating units (various)
	Splitting/Fractionation	REF_REG	UNIT	OP_MODE		Through-put volume: splitting/fractionation units (various)
	Non-fuel Processes	REF_REG	UNIT	OP_MODE		Through-put volume: processes not involved in fuels production
Operate	Hydrogen Prod/Rec	REF_REG	UTIL	OP_MODE		Volumes of hydrogen production and hydrogen recovery
Refinery	CHP Generation	REF_REG	UTIL	OP_MODE		Through-put volume to CHP units
Utilities	Refinery Fuel	REF_REG	UTIL	OP_MODE		Volume of refinery stream burned as refinery fuel
Transfer Refinery Streams		REF_REG	STR_TRAN			Volume of refinery stream transfer (analogous to a swing cut)
Specification Blending	Gasoline BOBs	REF_REG	GASB	I_STREAM		Volume of gasoline blendstock sent to gasoline BOB pool
Allocate Blendstock	Jet	REF_REG	DIST	I_STREAM		Volume of blendstock sent to jet pool
Volumes to Products	Distillates	REF_REG	DIST	I_STREAM		Volume of blendstock sent to a distillate pool (ex jet)
	Resid Fuels	REF_REG	RESID	I_STREAM		Volume of blendstock sent to a residual fuel pool
Specification Blending	Gasoline BOBs	REF_REG	GASB			Volume of gasoline BOB pool produced
Meet Product	Jet	REF_REG	DIST			Volume of jet pool produced
Specifications	Distillates	REF_REG	DIST			Volume of distillate fuel pool produced
	Resid Fuels	REF_REG	RESID			Volume of residual fuel pool produced
Recipe	Petchem Feedstocks	REF_REG	REC_PROD	REC_BLN		Volume of recipe-blended fuel produced
Blending	All Other Products	REF_REG	REC_PROD	REC_BLN		Volume of recipe-blended non-fuel product produced

Figure 6.9: Column Strip (Variable) Catalog (Continued)

	Ethanol (corn)	ALT_REG	RFS_FEED	RFS_PATH		Volume of corn ethanol production
Produce	Ethanol (sugar cane)	ALT_REG	RFS_FEED	RFS_PATH		Volume of sugar cane ethnol production
Renewable Fuels	Ethanol (cellulosic biomass	ALT_REG	RFS_FEED	RFS_PATH		Volume of cellulosic ethanol production
	Butanol (corn)	ALT_REG	RFS_FEED	RFS_PATH		Volume of butanol production
	Diesel (biomass based)	ALT_REG	RFS_FEED	RFS_PATH		Volume of biomass-based diesel production
	Diesel (cellulosic)	ALT_REG	RFS_FEED	RFS_PATH		Volume of cellulosic diesel production
	Other	ALT_REG	RFS_FEED	RFS_PATH		Volume of other biofuels production
Produce	CTL	ALT_REG	ALT_FEED	ALT_UNIT		Volume of CTL production
Alternative Fuels	GTL	ALT_REG	ALT_FEED	ALT_UNIT		Volume of GTL production
Import	Ethanol	DEM_REG	ETH_TYPE	PRICE	RFS_CAT	Volume of ethanol purchased, by type - imported
Biofuels Blendstocks	Biomass diesel	DEM_REG	ALT_FUEL	PRICE	RFS_CAT	Volume of advanced bio-fuel (ex ethanol) purchased, by type - imported
Meet RFS2 Mandates		REF_REG	RFS_CAT			Volume of EISA-mandated bio-fuel supplied, by type
Import	Gasoline BOBs	DEM_REG	GASB	PRICE	REGION	Volume of imported gasoline BOB
Finished	Diesel	DEM_REG	DIST	PRICE	REGION	Volume of imported distillate product
Products	All Others	DEM_REG	PROD	PRICE	REGION	Volume of imported refined product (ex gasoline BOBs and distillates)
	Gasoline BOBs	DEM_REG	REF_REG	GASO		Volume of gasoline BOBs transported from supply region to demand region
	Jet	DEM_REG	REF_REG	DIST		Volume of jet transported from supply region to demand region
Transport	Distillates	DEM_REG	REF_REG	DIST		Volume of distillates transported from supply region to demand region
Refined Products and	Resids	DEM_REG	REF_REG	RESID		Volume of resids transported from supply region to demand region
Alternative Fuels to	Petrochem feeds	DEM_REG	REF_REG	REC_PROD		Volume of petrochem feeds transported from supply region to demand region
Demand Regions	All other products	DEM_REG	REF_REG	REC_PROD		Volume of other refined products transported from supply region to demand region
	Ethanol	DEM_REG	ALT_REG	RFS_CAT		Volume of ethanol transported from supply region to demand region
	Butanol	DEM_REG	ALT_REG	RFS_CAT		Volume of butanol transported from supply region to demand region
	Biodiesel	DEM_REG	ALT_REG	RFS_CAt		Volume of biodiesel transported from supply region to demand region
	CTL	DEM_REG	ALT_REG	ALT_FUEL		Volume of CTL transported from supply region to demand region
	GTL	DEM_REG	ALT_REG	ALT_FUEL		Volume of GTL transported from supply region to demand region
Recipe	Gasoline	DEM_REG	PROD_T	REC_OPT		Volume of finished gasoline produced by terminal blending
Blend	E85	DEM_REG	PROD_T	REC_OPT		Volume of finished E85 produced by terminal blending
at Terminal	Biodiesel	DEM_REG	PROD_T	REC_OPT		Volume of finished diesel fuel produced by terminal blending
Supply	Export	REF_REG	PROD	TR_MODE		Volume of finished product exported
Finished Products	Domestic	DEM_REG	PROD			Volume of finished product supplied to domestic end-use region

Figure 6.10: Row Strip (Constraint) Catalog

Constraint Classes		Attributes			Description
Accounting Balances	Revenues	REGION	ACCNTG		Sums revenues from product sales over products and demand regions
	Input costs	REGION	ACCNTG		Sums costs of refinery inputs over input streams and refining regions
	Variable op costs	REGION	ACCNTG		Sums direct costs of refining and transport operations over streams, regions, and links
	Capital costs	REGION	ACCNTG		Sums capital costs associated with investments in refining and transport capacity
Energy / CO2 Balances	Energy Use	REF_REG	NRG_REF		Sums refinery energy use over energy inputs, refining processes and refining regions
	CO2 Output	REF_REG	CO2_SRC		Sums refinery emissions of CO2 over CO2 sources and refining region
Capacity Balances	Refining Capacity	REF_REG	UNIT		Llimits refining process unit capacity utilization to be < available capacity (existing + new + retrofit - shut down)
	Refining Capacity S/D	REF_REG	UNIT		Sets upper bound on slack crude running capacity, which triggers shut-down of excess slack capacity
	Refining Investment	REF_REG			Limits total investment in new refining capacity, by refining region, to be ≤ specified amount
	Alternative Fuels Capacity	ALT_REG	ALT_UNIT		Limits alternative fuels process capacity utilization to < available capacity (existing + new + retrofit_
	Alternative Fuels Invest.	ALT_REG			Limits total investment in new alternative fuels capacity, by alternative fuels region, to be ≤ specified amount
	Transport Capacity	REF_REG	TR_MODE	TR_SEG	Limits transport capacity utilization, by region, mode, and link, to be ≤ availabie capacity (existing + new)
	Transport Investment		TR_MODE		Limits total investment in new transport capacity, by mode, to be ≤ specified amount
Refinery Input Stream Limits	NGL	REF_REG	REF_INP		Limits regional and total supply of NGL to be ≤ specified volume
	Crude Oil	REF_REG	SOURCE	CRUDE	Limits regional and total supply of crude oil to be ≤ specified supply (function or limit)
	Unfinished Oils	REF_REG	SOURCE	UNF_OIL	Limits regional and total supply of unfinished oil to ≤ specified supply (function or limit)
	Blendstocks	REF_REG	SOURCE	BLN_STK	Limits regional and total supply of blendstock to < specified supply (function or limit)
	Alternative Fuels	REF_REG	SOURCE	ALT_FUEL	Limits regional and total supply of alternative fuel to < specified supply (function or limit)
Refinery Input Stream Balances	NGL	REF_REG	REF_INP		Equates volume of NGL acquired to volume transported to refining region
	Crude Oil	REF_REG	CRUDE		Equates volume of crude oil acquired to volume transported to refining region
	Unfinished Oils	REF_REG	UNF_OIL		Equates volume of unfinished oil purchased to volume transported to refining region
	Blendstocks	REF_REG	BLN_STK		Equates volume of blendstock purchased to volume transported to refining region
	Alternative Fuels	REF_REG	ALT_FUEL		Equates volume of alternative fuel purchased to volume transported to refining region
Refinery Input / Output Balances (Volumetric)	Refinery Inputs	REF_REG			
	Crude oil	REF_REG	SOURCE	CRUDE	Equates supply of crude oil to input to crude distillation unit
	NGL	REF_REG	I_STREAM		Equates supply of NGL to refining region utilization of NGL
	Intermediate Strms	REF_REG	I_STREAM		Equates production/supply of refinery intermediate stream to consumption of that stream
	Refinery Out-turns	REF_REG			
	Gasoline BOBs	REF_REG	GASO		Equates refinery production and dispatch of gasoline BOB
	Jet	REF_REG	DIST		Equates refinery production and dispatch of jet fuel
	Distillates	REF_REG	DIST		Equates refinery production and dispatch of distillate product (e.g., ULSD)
	Resids	REF_REG	RESID		Equates refinery production and dispatch of residual oil product
	Petchem feeds	REF_REG	REC_PROD		Equates refinery production and dispatch of petrochemical feedstock (recipe-blended)
	All other products	REF_REG	REC_PROD		Equates refinery production and dispatch of miscellaneous refined product (e.g., lubes and waxes)
Refinery Blending Volume Balances	Gasoline BOBs	REF_REG	GASO		Equates the total volume of all gasoline blendstocks supplied to a gasoline BOB pool to the volume of that pool
	Jet	REF_REG	DIST		Equates the total volume of all blendstocks supplied to the jet pool to the volume of that pool
	Distillates	REF_REG	DIST		Equates the total volume of all blendstocks supplied to a distillate pool to the volume of that pool
	Resids	REF_REG	RESID		Equates the total volume of all blendstocks supplied to a resid pool to the volume of that pool
Refinery Blending Specification Balances	Gasoline BOBs	REF_REG	GASO	QUAL_G	Equates the total quality-volume of all gasoline blendstocks supplied to a gasoline BOB pool to the specification-volume of that pc
	Jet	REF_REG	DIST	QUAL_D	Equates the total quality-volume of all blendstocks supplied to the jet pool to the specification-volume of that pool
	Distillates	REF_REG	DIST	QUAL_D	Equates the total quality-volume of all blendstocks supplied to a distillate pool to the specification-volume of that pool
	Resids	REF_REG	RESID	QUAL_R	Equates the total quality-volume of all blendstocks supplied to a resid pool to the specification volume of that pool
Alternative Fuels Production Input Stream Balances	Corn	ALT_REG	RFS_FEED		Equates volume of feed purchased to volume used in ethanol and biobutanol production
	Sugar Cane	ALT_REG	RFS_FEED		Equates volume of feed purchased to volume used in ethanol production
	Biomass solids	ALT_REG	RFS_FEED		Equates volume of feed purchased to volume used in ethanol production
	Biomass oils	ALT_REG	RFS_FEED		Equates volume of feed purchased to volume used in biomass-based diesel production
	Coal	ALT_REG	HC_FEED		Equates volume of coal purchased to volume used in CTL production
	Natural Gas	ALT_REG	HC_FEED		Equates volume of natural gas purchased to volume used in GTL production
Alternative Fuels Product Balances	Ethanol	ALT_REG	RFS_CAT	ETH_TYPE	Equates volume of ethanol produced, by RFS category, to volume transported to demand location
	Butanol	ALT_REG	RFS_CAT		Equates volume of butanol produced to volume transported to demand location
	Diesel	ALT_REG	RFS_CAT		Equates volume of biodiesel produced, by RFS category, to volume transported to demand location
	Other	ALT_REG	RFS_CAT		Equates volume of other renewable fuels produced, by RFS category, to volume transported to demand location
	CTL	ALT_REG	ALT_FUEL		Equates volume of CTL produced to volume transported to demand location
	GTL	ALT_REG	ALT_FUEL		Equates volume of GTL produced to volume transported to demand location
Special Constraints	Δ Crude oil quality	REF_REG	SPC_CONT		Constrains average quality (Sul and Sp.Gr.) of the crude oil pool to be within specified range of previous year's quality
	Technical (refining)	REF_REG	SPC_CONT		Various
	Technical (alt fuels)	EISA_CAT	RFS_CAT		Various
Terminal Blending Balances	Gasoline BOBs	DEM_REG	GASO		Equates volume of gasoline delivered to end use region to the volume of demand
	Distillates	DEM_REG	DIST		Equates volume of distillates delivered to end use region to the volume of demand
	Ethanol	DEM_REG	RFS_CAT		Equates volume of distillates delivered to end use region to the volume of demand
	Butanol	DEM_REG	RFS_CAT		Equates volume of butanol delivered to end use region to the volume of demand
	Biodiesel	DEM_REG	RFS_CAT		Equates volume of biodiesel delivered to end use region to the volume of demand
Policy Constraints	Policy (enviro)	SPC_CONE	REGION		Various
	Policy (refining)	SPC_CONR	REGION		Various
	Policy (transport)	SPC_CONT	REGION		Various
Product Demand Balances	Gasoline	DEM_REG	PROD		Sets the sum of imports and domestic supply of finished gasoline type ≥ specified demand
	E85	DEM_REG	PROD		Sets the total volume of domestic E85 supply ≥ specified demand
	Jet	DEM_REG	PROD		Sets the sum of imports and domestic supply of jet fuel ≥ specified demand
	Distillates	DEM_REG	PROD		Sets the sum of imports and domestic supply of distillate fuel ≥ specified demand
	Resids	DEM_REG	PROD		Sets the sum of imports and domestic supply of residual fuel ≥ specified demand
	Petrochem feeds	DEM_REG	PROD		Sets the sum of imports and domestic supply of petrochem feeds ≥ specified demand
	All other products	DEM_REG	PROD		Sets the sume of imports and domestic supply of all other refined products ≥ specified demand
Upper Bounds Lower Bounds					

Mathematical Representation of Model Design

The LFMM will be a multiple time period, multi-region, linear programming model. It will be designed to return solutions that:

1. Meet specified volume requirements for all liquid fuels in all regions in all time periods.
2. Satisfy all other specified constraints.
3. Minimize the total delivered cost in nominal dollars to satisfy all liquid fuels volume requirements.

All costs subject to minimization appear in the model's objective function in Section Chapter 0.

It is worth noting at this point that the LFMM objective function could also be formulated to maximize profit as opposed to minimizing the cost of satisfying demand. This could be accomplished by setting up demand curves for the end-use products, such as E10 gasoline, which would reflect how the NEMS transportation model product demands may change in response to varying product prices. This profit-maximization approach would allow the LFMM some product pricing flexibility, which is one advantage it has over the aforementioned minimum-cost approach. While it is likely that model development will involve experimentation with both of these approaches in the prototyping phase, for the sake of brevity, this documentation includes a mathematical specification only for the minimum-cost approach.

Because this will be a multi-period model, it is important to note certain details regarding the discounting of future information:

- Each price/cost in the LP formulation will be calculated as an *average nominal unit price* discounted to the beginning of the full projection horizon. This average is computed as the net present value (NPV) of the nominal unit price in each year associated with a given projection period, divided by the net present value of one unit of product over the same time period.

- All constraint right-hand sides and bounds (product demands, RFS constraints, etc.) in a given planning period are calculated as the NPV of the values associated with each year of that planning horizon and then discounted to the beginning of the full projection horizon.

More detail regarding capital investments may be found in Section Chapter 0.

Index Definitions

a ≡ Index of refinery processes as listed in **Figure 5.8.**
b ≡ Index of blend stocks as listed in **Figure 5.7**.
c ≡ Index of refinery co-products such as electricity and dried distillers grains with solubles (DDGS).

d ≡ Index of product demand regions (Census Regions).
e ≡ Index of crude oil types, foreign and domestic.
g ≡ Index of utility-generating refinery processes.
i ≡ Index of utilities purchased by refineries.
j ≡ Index of air pollutants emitted by refineries.
m ≡ Index of transportation modes as listed in **Figure 5.14**.
n ≡ Index of refinery process operating modes.
p ≡ Index of refinery-produced products, either for direct use or for blending.
r ≡ Index of refining regions as listed in **Figure 5.5.**
s ≡ Index of feed stocks to be purchased by refineries.
t ≡ Index of refinery types (e.g. cracking, coking, etc.).
w ≡ Index of specification blending recipes for blended products.
x ≡ Index of time periods.

Column Definitions

$B_{b,r,x}$ ≡ Quantity of imported blend stock (b) purchased in refining region (r) in planning period (x).
$CC_{r,x}$ ≡ Accounting variable representing the total capital cost from capacity expansion in refining region (r) in planning period (x).
$CP_{c,r,x}$ ≡ Quantity of refining co-product (c) sold in refining region (r) in planning period (x). Co-products include electricity co-generation, DDGS from corn ethanol production, etc.
$E_{i,r,x}$ ≡ Quantity of utility (i) purchased in refining region (r) in planning period (x).
$ET_{r,r',m,x}$ ≡ Existing capacity of transportation mode (m) between refining regions (r) and (r') in planning period (x).
$ET_{r,d,m,x}$ ≡ Existing capacity of transportation mode (m) between refining region (r) and demand region (d) in planning period (x).
$F_{s,r,x}$ ≡ Quantity of feed stock (s) purchased in refining region (r) in planning period (x).
$G_{p,t,d,x}$ ≡ Volume of refined product (p) that is used directly (without blending) to satisfy demand for finished product (t) in demand region (d) in planning period (x). It is worth noting that these vectors only exist when p=t.
$I_{p,r,x}$ ≡ Quantity of imported finished product (p) purchased in refining region (r) in planning period (x).
$IC_{r,x}$ ≡ Accounting variable representing the total input costs in refining region (r) in planning period (x).
$L_{a,t,r,x}$ ≡ Existing capacity for refinery process (a) in refinery type (t) in refining region (r) that may be used in all planning periods up to and including (x).
$O_{a,t,r,n,x}$ ≡ Operation of refinery process (a) in refinery type (t) in refining region (r) in operating mode n in planning period (x).
$O_{g,t,r,n,x}$ ≡ Operation of utility generating refinery process (g) in refinery type (t) in refining region (r) in operating mode (n) in planning period (x).
$P_{i,p,r,t,x}$ ≡ Volume of intermediate stream (i) sent to product blending pool (p) in refinery type (t) in refining region (r) in planning period (x).

$Q_{p,t,r,x}$ ≡ Volume of refined product (p) produced in refinery type (t) in refining region (r) in planning period (x).
R_r ≡ Accounting variable representing the total revenue from product exports and co-product sales in refining region (r) in planning period (x).
$RF_{a,a',t,r,x}$ ≡ Existing capacity of refinery process (a) that has been retrofitted to capacity of refinery process (a') in refinery type (t) in refining region (r) in planning period (x).
$T_{i,r,r',m,x}$ ≡ Quantity of intermediate product or crude (i) transported from refining region (r) to refining region (r') using transportation mode (m) in planning period (x).
$T_{p,r,d,m,x}$ ≡ Quantity of refined product (p) transported from refining region (r) to demand region (d) using transportation mode (m) in planning period (x).
$TC_{r,x}$ ≡ Accounting variable representing the total transport costs of moving products and/or crude oil out of refining region (r) in planning period (x).
$U_{e,r,t,x}$ ≡ Quantity of crude oil of type (e) imported into in refining region (r) used in refinery type (t) in planning period (x).
$V_{p,r,m,x}$ ≡ Quantity of product (p) exported from refining region (r) using transportation mode (m) in planning period (x).
$VC_{r,x}$ ≡ Accounting variable representing the total variable operating costs in refining region (r) in planning period (x).
$W_{i,r,t,x}$ ≡ Quantity of non-crude refinery input stream (i) imported into in refining region (r) used in refinery type (t) in planning period (x).
$X_{a,t,r,x}$ ≡ Capacity expansion activity for refinery process (a) in refinery type (t) in refining region (r) in planning period (x) that may be used in all subsequent planning periods.
$XT_{r,r',m,x}$ ≡ Capacity expansion activity for transportation mode (m) between refining regions (r) and (r') in planning period (x).
$XT_{r,d,m,x}$ ≡ Capacity expansion activity for transportation mode (m) between refining region (r) and demand region (d) in planning period (x).
$Y_{j,r,x}$ ≡ Quantity of air pollutant (j) emitted in refining region (r) in planning period (x).
$Z_{p,t,w,d,x}$ ≡ Amount of terminal-blended product (t) produced in demand region (d) using refined product (d) using recipe (w) in planning period (x).

Objective Function

The objective function seeks to minimize total costs minus revenues over all refining regions (r) and planning periods (x).

$$\text{Minimize} \sum_r \sum_x \{IC_{r,x} + VC_{r,x} + CC_{r,x} + TC_{r,x} - R_{r,x}\}$$

Row Constraints

1. Revenue accounting for each refining region (r) and planning period (x)

$$R_{r,x} - \sum_m \sum_p XPR_{p,r,x} V_{p,r,m,x} - \sum_c PR_{c,r,x} * CP_{c,r,x} = 0$$

where

- $XPR_{p,r,x}$ ≡ Average nominal unit export price of product (p) in refining region (r) in planning period (x).
- $PR_{c,r,x}$ ≡ Average nominal unit price of co-product (c) in refining region (r) in planning period (x).

I.e., the total revenue for a given refining region in planning period (x) must equal the sum of the revenue from export product sales through all transportation modes (m) and the sum of the revenue from the sales of refining co-products.

2. Input cost accounting for each refining region (r) and planning period (x)

$$IC_{r,x} - \sum_{e}\sum_{t} PR_{e,r,x} * U_{e,r,t,x} - \sum_{b} PR_{b,r,x} * B_{b,r,x} - \sum_{p} PR_{p,r,x} * I_{p,r,x} - \sum_{s} PR_{s,r,x} * F_{s,r,x} = 0$$

where

- $PR_{e,r,x}$ ≡ Average nominal purchase price of crude of type (d) from source (s) in refining region (r) in planning period (x).
- $PR_{b,r,x}$ ≡ Average nominal price of imported blend stock (b) in refining region (r) in planning period (x).
- $PR_{p,r,x}$ ≡ Average nominal price of imported finished product (p) in refining region (r) in planning period (x).
- $PR_{s,r,x}$ ≡ Average nominal price of feedstock (s) in refining region (r) in planning period (x).

I.e., for each planning period, the total input cost for a given refining region must equal the sum of all refinery purchases including refinery fuel, imported crude oil, blend stocks, product imports, and feed stocks.

3. Variable operating cost accounting for each refining region (r) and planning period (x)

$$VC_{r,x} - \sum_{a}\sum_{t}\sum_{n} VC_{a,t,r,n,x} * O_{a,t,r,n,x} - \sum_{i} PR_{i,r,x} * E_{i,r,x} = 0$$

where

- $VC_{a,t,r,x}$ ≡ Average nominal variable operating cost of refinery process (a) in refinery type (t) in refining region (r) in operating mode (n) in planning period (x).
- $PR_{i,r,x}$ ≡ Average nominal price of utility (i) in refining region (r) in planning period (x).

I.e., for each planning period, the total variable operating cost for a given refining region must equal the sum of variable operating costs over all refinery processes over all refinery types plus all refinery utility purchases.

4. Transportation cost accounting for each refining region (r) and planning period (x)

$$TC_{r,x} - \sum_{r'} \sum_{i} \sum_{m} TC_{i,r,r',m,x} * T_{i,r,r',m,x} - \sum_{d} \sum_{p} \sum_{m} TC_{p,r,d,m,x} * T_{p,r,d,m,x} = 0$$

where

- $TC_{i,r,r',m,x}$ ≡ Average nominal cost of transporting intermediate product or crude oil (i) from refining region (r) to refining region (r') using transportation mode (m) in planning period (x).
- $TC_{p,r,d,m,x}$ ≡ Average nominal cost of transporting finished product (p) from refining region (r) to demand region (p) using transportation link (m) in planning period (x).

I.e., for each planning period, the total transportation cost for a given refining region must equal the sum of all transportation costs incurred moving both intermediate and finished products out of that refining region.

5. Capital cost accounting for each refining region (r) and planning period (x)

$$CC_{r,x} - \sum_{a} \sum_{t} XC_{a,t,r,x} * X_{a,t,r,x} - \sum_{r'} \sum_{m} XTC_{r,r',m,x} * XT_{r,r',m,x} - \sum_{d} \sum_{m} XTC_{r,d,m,x} * XT_{r,d,m,x} = 0$$

where

- $XC_{a,t,r,x}$ ≡ Levelized capital cost of capacity expansion of refinery process (a) in refinery type (t) in refining region (r) in planning period (x).
- $XTC_{r,r',m,x}$ ≡ Levelized capital cost of capacity expansion of transportation mode (m) between refinery regions (r) and (r') in planning period (x).
- $XTC_{r,d,m,x}$ ≡ Levelized capital cost of capacity expansion of transportation mode (m) between refinery regions (r) and (d) in planning period (x).

I.e., for each planning period, the total capital cost for a given refining region must equal the sum of all capital costs from refining process capacity expansion in that region over all refinery types plus all capital costs from the expansion of transportation link capacity originating in that region.

NOTE: Although this documentation includes transportation capacity expansion in its formulation here, that value will likely not be allowed in the initial versions of the LFMM.

6. Refinery energy use balance for each refining region (r) and utility type (i) and planning period (x)

$$E_{i,r,x} + \sum_{g} \sum_{t} \sum_{n} EG_{i,g,t,r,n,x} * O_{g,t,r,n,x} - \sum_{a} \sum_{t} EU_{i,a,t,r,n,x} * O_{a,t,r,n,x} = 0$$

where

- $EG_{i,g,t,r,n,x}$ ≡ Amount of utility (i) generated by utility generating unit (g) in refinery type (t) in refining region (r) in operating mode (n) in planning period (x).
- $EU_{i,a,t,r,n,x}$ ≡ Amount of utility (i) consumed by refinery process (a) in refinery type (t) in refining region (r) in operating mode (n) in planning period (x).

I.e., for each planning period, for each refinery region (r) and utility type (i), the purchase of that utility plus the refinery manufacture of that utility must equal the consumption of that utility over all refinery processing units in all refinery types.

7. Refinery emissions balance for each refining region (r) ,air pollutant (j), and planning period (x)

$$Y_{j,r,x} - \sum_{a}\sum_{t}\sum_{n} EM_{j,a,t,r,n,x} * O_{a,t,r,n,x} - \sum_{g}\sum_{t}\sum_{n} EM_{j,g,t,r,n,x} * O_{g,t,r,n,x} = 0$$

where

- $EM_{j,a,t,r,n,x}$ ≡ Quantity of air pollutant (j) generated by refinery process (a) in refinery type (t) in refining region (r) in operating mode (n) in planning period (x).
- $EM_{j,g,t,r,n,x}$ ≡ Quantity of air pollutant (j) generated by utility generating refinery process (g) in refinery type (t) in refining region (r) in operating mode (n) in planning period (x).

I.e., for each planning period (x), the total emission of pollutant type (j) in refinery region (r) is the sum of the emissions over all refinery processes in all refinery types.

8. Existing capacity balance over all planning periods for each refinery process (a), refining region (r), and refinery type (t)

$$\sum_{x} L_{a,t,r,x} - \hat{L}_{a,t,r} = 0$$

where

- $\hat{L}_{a,t,r}$ ≡ Base existing capacity of refinery process (a) in refinery type (t) in refining region (r) carried over from the previous model year. It is worth noting that for a given model year, the base existing capacity for a given refinery process is the amount of existing capacity that was used for at least the first two planning periods of the last model year, i.e.

$$\hat{L}_{a,t,r} \equiv \sum_{x>1} L_{a,t,r,x}^{(year-1)}$$

I.e., the sum of the existing capacity either (1) used in the first period and then retired, (2) used in periods 1 and 2 and then retired, or used in all periods must equal the amount of base existing capacity coming into a given model year. The retirements will be applied to distillation units directly, with downstream capacity getting reduced proportionally.

9. Refining process capacity balances for each refining region (r), refinery type (t), refinery processing unit (a), and planning period (x)

$$- \sum_{x'=1}^{x} L_{a,t,r,x'} - \sum_{x'=1}^{x} CF_{a,t,x'} * X_{a,t,r,x'} - \sum_{x'=1}^{x}\sum_{a' \neq a} RF_{a',a,t,r,x'} + \sum_{x'=1}^{x}\sum_{a' \neq a} RF_{a,a',t,r,x'} + \sum_{n} O_{a,t,r,n,x} \leq 0$$

where

- $CF_{a,t} \equiv$ Capacity factor of refinery process (a) in refinery type (t).

I.e., for each planning period, the operation of refinery process (a) in refinery type (t) in region (r) over all modes of operation (n) must be less than or equal to the sum of the base existing capacity plus new capacity-factor-adjusted capacity expansion in all planning periods through the current one plus capacity from any other processes (a') that was converted through retrofitting to this process in all planning periods, through the current one, minus any existing capacity of this process that has been retrofitted to any other processes (a') in all planning periods through the current one.

10. Limit on total refinery investment for refinery type (t) in refining region (r) in planning period (x)

$$\sum_{r'}\sum_{m} XC_{a,t,r,x} * X_{a,t,r,x} - IL_{t,r,x} \leq 0$$

where

- $XC_{a,t,r,x} \equiv$ Levelized capital cost of capacity expansion of refinery process (a) in refinery type (t) in refining region (r) in planning period (x).
- $IL_{t,r,x} \equiv$ Maximum allowed investment in refinery process capacity expansion for refinery type (t) in refining region (r) in planning period (x).

I.e., for each planning period (x), the total investment for refinery process capacity expansion in refinery type (t) in refining region (r) cannot exceed the specified limit.

11. Transportation capacity bounds for each allowable refinery region to refinery region origin-destination pair (r,r'), transportation mode (m), and planning period (x)

$$-CF_{r,r',m,x} * \left(ET_{r,r',m,x} + XT_{r,r',m,x}\right) + \sum_{i} T_{i,r,r',m,x} \leq 0$$

where

- $CF_{r,r',m,x} \equiv$ Capacity factor of transportation link of mode type (m) between refinery regions (r) and (r') in planning period (x).

I.e., for each planning period, the total finished product, intermediate product, and crude oil transported between refining regions (r) and (r') using transportation mode (m) must not exceed the maximum capacity of that transportation link.

12. Transportation capacity bounds for each allowable refinery region to demand region origin-destination pair (r,d), transportation mode (m), and planning period (x)

$$-CF_{r,d,m,x} * \left(ET_{r,d,m,x} + XT_{r,d,m,x}\right) + \sum_{i} T_{i,r,d,m,x} \leq 0$$

where

- $CF_{r,d,m,x} \equiv$ Capacity factor of transportation link of mode type (m) between refinery region (r) and demand region (d) in planning period (x).

I.e., for each planning period, the total finished product, intermediate product, or crude oil transported between refining region (r) and demand region (d) using transportation mode (m) must not exceed the maximum capacity of that transportation link.

13. Limit on total transportation capacity investment for refinery region (r) in planning period (x)

$$\sum_{r'}\sum_{m} XTC_{r,r',m,x} * XT_{r,r',m,x} - \sum_{d}\sum_{m} XTC_{r,d,m,x} * XT_{r,d,m,x} - TL_{t,r,x} \leq 0$$

where

- $TL_{t,r,x}$ ≡ Maximum allowed investment in transportation capacity expansion in refining region (r) in planning period (x).
- $XTC_{r,r',m,x}$ ≡ Levelized capital cost of capacity expansion of transportation mode (m) between refinery regions (r) and (r') in planning period (x).
- $XTC_{r,d,m,x}$ ≡ Levelized capital cost of capacity expansion of transportation mode (m) between refinery region (r) and demand region (d) in planning period (x).

I.e., for each planning period, the total investment for transportation capacity expansion in refining region (r) cannot exceed the specified limit.

14. Refinery input crude oil balances for each refining region (r), crude type (e), and planning period (x)

$$\sum_{t} U_{e,r,t,x} - \sum_{r'}\sum_{m} T_{e,r',r,m,x} + \sum_{r'}\sum_{m} T_{e,r,r',m,x} = 0$$

where

- i ≡ Index of transported product stream corresponding to crude oil.

I.e., for each planning period, the total supply of crude oil of type (e) in a refining region (r) at all refinery types (t) must equal the amount transported in minus the amount transported out.

Note: There would be a similar constraint for each refinery input stream (e.g. unfinished oil, blend stocks, etc.).

15. Refinery non-crude input balances for each refining region (r), non-crude input stream (i), and planning period (x)

$$\sum_{t} W_{i,r,t,x} - \sum_{r'}\sum_{m} T_{i,r',r,m,x} + \sum_{r'}\sum_{m} T_{i,r,r',m,x} = 0$$

where

- i ≡ Set of all other non-crude refinery input streams.

I.e., for each planning period, the total supply of non-crude refinery input stream (i) in a refining region (r) over all refinery types (t) must equal the amount transported in minus the amount transported out.

16. Refinery input crude/ACU operate balance for refinery type (t), refining region (r), crude type (e), and planning period (x)

$$-U_{e,r,t,x} + O_{ACU,t,r,d,x} = 0$$

I.e., for each planning period, the total volume of crude type (e) processed in the ACU unit of refinery type (t) in refining region (r) must be equal to the total crude of type (d) supplied to that refinery. It is worth noting here that the "operating mode" of ACU and VCU are defined by the crude type being processed.

17. Refinery input crude/VCU operate balance for refinery type (t), refining region (r), crude type (e), and planning period (x)

$$-VAC_{e,r,t,x} * U_{e,r,t,x} + O_{VCU,t,r,e,x} = 0$$

where

- $VAC_{e,r,t,x}$ ≡ Fraction of total crude volume input of crude type (e) to the ACU unit in refinery type (t) in refining region (r) that is input to the vacuum distillation unit (VCU) in planning period (x).

I.e., for each planning period, the total volume of crude of type (e) processed in the vacuum distillation unit of refinery type (t) in refining region (r) must be equal to the residual fraction of the total crude processed in the ACU unit at that refinery.

18. Intermediate stream balance for each stream (i), refinery type (t), refining region (r), and planning period (x)

$$-W_{i,r,t,x} - \sum_{u=ACU,VCU} \sum_{d} YLD_{i,u,d,r,t,x} * O_{u,t,r,d,x} - \sum_{a} \sum_{n} YLD_{i,a,n,r,t,x} * O_{a,t,r,n,x} + \sum_{p} P_{i,p,r,t,x} = 0$$

where

- $YLD_{i,u,d,r,t,x}$ ≡ The yield of intermediate stream (i) by crude distillation process (u) using input crude (d) in refinery type (t) in refining region (r) in planning period (x).
- $YLD_{i,a,n,r,t,x}$ ≡ The yield (if positive) or consumption (if negative) of intermediate stream (i) by downstream refining process (a) in operating mode (n) in refinery type (t) in refining region (r) in planning period (x).

I.e., for each planning period, the volume of intermediate stream (i) in refinery type (t) in refining region (r) consumed by processing units and sent to product blending pools must be equal to the sum of the imports of that stream, the amount of that stream produced by the distillation units, and the amount produced by other downstream processes across all operating modes.

19. Refinery product output/transport balances for each refined product (p) , refining region (r), and planning period (x)

$$-\sum_{t} Q_{p,t,r,x} - I_{p,r,x} + \sum_{d}\sum_{m} T_{p,r,d,m,x} + \sum_{m} V_{p,r,m,x} = 0$$

I.e., for each planning period, the total volume of refined product (p) transported out of refining region (r) plus refined product exported out of refining region (r) over all transportation modes must be equal to the sum of the volume of that product produced in that region across all refinery types (t) and the amount of that product imported into that refining region.

20. Quality control for specification blends for product (p), specification quality (q), refinery type (t), refining region (r), and planning period (x)

$$-\sum_{i} QUAL_{q,i,r,t,x} * P_{i,p,r,t,x} + SPEC_{q,p,r,x} * Q_{p,t,r,x} \leq 0$$

where

- $QUAL_{q,i,r,t,x}$ ≡ Quality value for quality (q) for intermediate stream (i) in refinery type (t) in refinery region (r) in planning period (x).
- $SPEC_{q,p,r,x}$ ≡ Minimum value of quality (q) required for refined product (p) in refinery region (r) in planning period (x).

I.e., for each planning period, the minimum quality specifications (q) for all specification blended products (p) must be complied with at each refinery type in each refining region.

21. Refinery blending volume balances for each product (p), refinery type (t), refining region (r), and planning period (x)

$$-\sum_{i} P_{i,p,r,t,x} + Q_{p,t,r,x} = 0$$

I.e., for each planning period, the sum of the inputs to the product blending pools for product (p) must be equal to the amount of refined product produced at refinery type (t) in refining region (r).

22. Crude oil minimum and maximum quality constraints for each crude quality (q), refining region (r), and planning period (x)

$$-\sum_{e}\sum_{t} QUAL_{q,e,r,x} * U_{e,r,t,x} + SPEC^{min}_{q,e,r,x} * \sum_{e}\sum_{t} U_{e,r,t,x} \leq 0$$

and

$$\sum_{e}\sum_{t} QUAL_{q,e,r,x} * U_{e,r,t,x} - SPEC^{max}_{q,e,r,x} * \sum_{e}\sum_{t} U_{e,r,t,x} \leq 0$$

where

- $QUAL_{q,e,r,x}$ ≡ Value of quality (q) for crude type (e) in region (r) in planning period (x).
- $SPEC^{min}_{q,e,r,x}$ ≡ Minimum allowed value of quality (q) for crude type (e) in region (r) in planning period (x).
- $SPEC^{max}_{q,e,r,x}$ ≡ Maximum allowed value of quality (q) for crude type (e) in region (r) in planning period (x).

I.e., for each planning period, the average value of crude quality (q) over all crude used in refining region (r) must be within a specified range as derived from the previous year's average quality.

23. Technical refinery process constraints for each refinery process (a), operating mode (n), intermediate stream (i), refinery type (t), refining region (r), and planning period (x)

$$-YLD_{i,a,n,r,t,x} * O_{a,t,r,n,x} - TECH_{i,a,n,r,t,x} * O_{a,t,r,n,x} \leq 0$$

where

- $TECH_{i,a,n,r,t,x}$ ≡ The maximum consumption of intermediate stream (i) by downstream refining process (a) in operating mode (n) in refinery type (t) in refining region (r) in planning period (x).
- $YLD_{i,a,n,r,t,x}$ ≡ The yield (if positive) or consumption (if negative) of intermediate stream (i) by downstream refining process (a) in operating mode (n) in refinery type (t) in refining region (r) in planning period (x).
- $YLD_{i,a,n,r,t,x} \leq 0$; i.e., this is a yield factor that represents consumption.

These constraints comprise individual technical restrictions on refinery processes, such as: "The total vacuum residuum feed to the Fluid Catalytic Cracking unit may not exceed some percentage of the total feed to that unit." The above constraint is only one example of a technical refinery process constraint; a complete list is beyond the scope of this CDR and will be specified during the prototyping phase.

24. Volume balances for each refined product (p), blending recipe (w), demand region (d), and planning period (x)

$$-\sum_{r}\sum_{m} T_{p,r,d,m,x} + G_{p,t,d,x} + \sum_{t} BR_{p,t,w,d} * Z_{p,t,w,d,x} = 0$$

where

- $BR_{p,t,w,d}$ ≡ Volumetric fraction of refined product (p) contained in finished product (t) using recipe (w) in demand region (d).

I.e., for each planning period, the sum of the volume of refined product (p) used for blending into all terminal-blended products (t) using all recipes (w) in demand region (d) plus the volume of refined product (p) that may be directly used as finished product (t) without blending must be equal to the total of that refined product transported into that demand region from all refining regions over all transportation modes.

25. RFS/EISA mandates for each EISA category (C) and planning period (x)

$$-\sum_{p\in C}\sum_{t}\sum_{r} Q_{p,t,r,x} + RFS_C \leq 0$$

I.e., the sum of all products produced that qualify towards RFS category (C) must be greater than or equal to the mandated volume.

26. Satisfaction of finished product demands for each finished product (t), demand region (d), and planning period (x)

$$-G_{p,t,d,x} - \sum_{p}\sum_{w} Z_{p,t,w,d,x} + D_{t,d,x} = 0$$

I.e., the total volume of finished product (t) delivered to demand region (d) over both blended and unblended products must be equal to the product demand in that region.

Capacity Rationalization: Expansion and Retirement/Upgrades

Capacity expansion and retirements in the LFMM will be part of the LP solution process, and will be based on discounted multi-period economics and product demands, analogous to the NEMS Electricity Market Module. In other words, capacity expansion and rationalization will be determined by the least-cost mix of all costs, including capital, O&M, and fuel needed to satisfy a particular product demand slate over the projection horizon in a given model year.

Treatment/Capture of Average Costs versus Marginal Costs

The LFMM will generate marginal costs of production for each refinery product. However, because the model will use an LP, the *average* cost of production is not something that will be easily obtainable out of the LFMM.

Calibration and Benchmarking

The LFMM should be calibrated annually to the most recent year's reported operating results in each refining region represented in the model. (For example, if the LFMM were in operation now, it should be calibrated to 2009 reported operations before being used in the preparation of the 2011 *Annual Energy Outlook*.) The primary objective of each annual calibration is to demonstrate that the regional refining sub-models in the LFMM represent with desired accuracy the regional refining operations in the prior year – and therefore that the LFMM will be a credible analytical component of NEMS. In addition, experience indicates that calibration will sometimes reveal the need to update certain technical coefficients of the LFMM.

Calibrating a regional refining sector model such as the LFMM will involve adjusting some of the model's technical coefficients – such as yields of refinery streams from certain refining processes, blending properties of refinery streams, and (most commonly) process capacity utilization rates – as needed. The goal is to match, with sufficient precision, solutions returned by the model against key aggregate measures of regional refining operations and economics reported for the calibration period(s). The calibration should address both the summer and winter gasoline seasons.

Calibration is an iterative procedure. It involves the following steps:

- Establishing model inputs that correspond to reported inputs (e.g., crude slate, unfinished oils) to each refining region in the period of interest.
- Solving the model with those inputs.
- Comparing the results returned by the model to the reported regional refining outputs (product volumes, average properties, and average prices) of the refining regions being analyzed.
- Adjusting certain technical coefficients in the model, as needed
- Repeating the preceding steps until model outputs match with desired precision certain reported measures of regional refining operations. The most important of these reported measures include:

    - Production rates of the primary refined products;
    - Average properties of the gasoline and distillate pools;
    - Petroleum product prices, in general; and
    - Gasoline and distillate price differentials, in particular;
    - Operating severities (such as FCC conversion level and reforming severity); and
    - Refinery energy use.

Experience with other refining sector models indicates that the coefficients most likely to call for adjustment in the course of the calibration are:

- Process unit service factors, especially for conversion processes
- Process yields, especially for conversion processes
- Properties of upgraded or treated blendstocks

Often, the changes made to technical coefficients reflect changes in refining operations that occurred during the calibration year. These changes in operations may be transient (e.g., a spike in unit downtime due to turnarounds or unscheduled outages) or permanent (e.g., changes in process yields due to, for example, introduction of new catalysts). Thus, the calibration process contributes to and sometimes provides direction for the periodic updating of the technical data expressed in the model's coefficients.

Most of the historical operating data needed for calibrating the LFMM is available in DOE/EIA publications, such as the *Petroleum Supply Annual* and the *Petroleum Marketing Annual*; a handful of trade publications, such as the *Oil & Gas Journal*; and the *North American Fuel Surveys* published by the Alliance of Automobile Manufacturers. Data specific to the California refining sector is available in various California Energy Commission publications.

A caveat is in order. Calibration requires extensive analysis, manipulation, and re-organization of published data. It may involve numerous iterations (of the kind described above), and can trigger ad hoc efforts to gather new technical data. Consequently, model calibration can be time-consuming and tedious. However, it is an essential element of sound modeling practice.

Prototyping Objectives

The LFMM prototype will allow developers to test many alternate model designs without the overhead of being embedded in NEMS. Each alternative will have implications about the quality and robustness of the answers provided, as well as the time needed to achieve a solution. Prototyping will allow developers to map out the frontier between solution quality and solution time, and thus provide insight into to the following questions:

- What is the best way to model the rest of the world?
- Should this be a multi-time period model? If so, should the cost structure use a discount like the NEMS ECP does?
- What are the best regional definitions to use?
- Should price and demand elasticity be modeled?
- How many refinery types should be modeled?
- How many product categories should be represented?

It will be important to implement the LFMM prototype with sufficient robustness to the above key parameters so that different modeling approaches may be tested efficiently.

7. Foresight and Investment Planning

Foresighted versus Myopic Investment/Retirement Planning

Foresight in analyzing the liquid fuels market is an important theoretical and modeling consideration. First, one must decide whether foresight is appropriate at all, and if so, what form that foresight will take (e.g. perfect foresight, discounted foresight, etc.) An approach where it is assumed that the future is identical to the present is called "myopic" and investment decisions based on the myopic approach are termed "just-in-time."

The current PMM represents investment in new capacity using a three-year look-ahead with perfect foresight. Under this approach, a capacity expansion LP is executed every three years. It looks three years into the future and builds capacity based on what future values exist from previous NEMS cycles. After new capacity is built in the regular PMM iterations, these "capacity builds" have their expansion limited, based on the decisions made in the capacity expansion LP. This approach was implemented as a middle ground between a myopic approach and a multi-period approach, because the multi-period approach was considered to be too computationally intensive at the time PMM was first developed.

The LFMM will use a multi-period planning approach similar to the approach taken in the NEMS Electricity Market Model (EMM.) The multi-period approach has several advantages over a myopic approach. For example, the multi-period approach:

- Allows refineries make investment decisions with some knowledge of future legislation which may impact their business.[24] Examples of such legislation over the last twenty years include the Renewable Fuels Standard 2 (RFS2), Federal ultra-low sulfur diesel (ULSD), and MSAT2 for gasoline benzene control. Future legislative policies that may need to be addressed by NEMS include a low-carbon fuel standard (LCFS) and various carbon cap-and-trade or carbon tax policies.
- Reduces the chance of having large stranded assets as a result of short-term fluctuations in prices and demands.
- Allows capacity retirement decisions to be made on economic terms as opposed to some exogenous capacity utilization standard.
- Is more likely to produce "smooth" capacity expansion/retirement trajectories without large year-to-year changes.

The main advantages of the myopic approach, on the other hand, are that it is considerably simpler to implement and that it is less computationally intensive.

[24] Limitations of using the myopic approach are apparent, for example when to analyzing a policy that contains an escalating carbon tax. Under a myopic approach, there may be considerable investment in coal-to-liquids (CTL) capacity (to produce distillate fuels from coal) in the early years of the modeling horizon because it is cost-effective and the carbon tax is low in the current modeling year. However, these assets would likely be stranded in future years once the carbon tax reaches higher levels.

It may also be noted that the decision to build U.S. refining capacity will be highly dependent on the international product import supply curves input into the LFMM. In other words, the LFMM must determine how much of U.S. petroleum product demand will be met each year by domestic refinery output and how much will be met by product imports. This determination will depend on:

- U.S. refining capacity (including capacity additions in the current year)
- The marginal prices of domestic refinery output (including the contribution of capital charges associated with the capacity additions)
- The supply functions of imported petroleum products

Given the uncertainties inherent in the import supply functions (including the capacity available for supplying U.S. markets), an argument could be made that a relatively complex multi-period representation of capacity additions in domestic refineries may not be warranted in the LFMM.

On the balance, the multi-period approach has been chosen because it is thought to be a better fit for the policy analysis needs within the NEMS framework. However, it should be noted here that it would be relatively easy to revert back to the myopic approach once the multi-period approach is implemented. Doing so would involve simply setting the number of periods to one. Designing and implementing the LFMM as a multi-period model gives developers the ability to experiment with both the myopic and multi-period approaches.

Treatment of Expectations

The LFMM will use a discounted perfect foresight approach for future demand and price levels. All future inputs needed for a given model year will be taken from either (1) the NEMS restart file if the year is less than or equal to the NEMS final projection year, or (2) from various assumptions about future values if the year is after the final NEMS projection year. Assumptions about future year values past the NEMS projection horizon year may include trending, holding a value fixed after the final NEMS year, or having the values specified explicitly from an input file.

Treatment of Investments

The LFMM will use a traditional net present value (NPV) capital budgeting approach to evaluate investment decisions in each planning period similar to the approaches taken in the NEMS Electricity Market Module (EMM) and Hydrogen Market Module (HMM). That is, for a given period, the following steps will be taken to calculate an NPV $/bbl/day unit expansion cost:

1. A $/barrel/stream day nominal annuity will be calculated using an approach analogous to the one used in the EMM or HMM.
2. The NPV of the stream of annuities will be calculated over the number of years from the beginning of the current planning period to the end of the investment horizon, using a weighted-average cost of capital (WACC) as the discounting rate. If it is not the first planning period, this stream is then discounted back to the first period dollars.

Only investments made in the first planning period will be kept for subsequent model years; the others will be discarded.

8. Uncertainty and Limitations

Modeling the liquid fuels markets in NEMS presents a number of challenges that translate into limitations and uncertainty in the resulting projections. This section will discuss briefly some of the more significant uncertainty and limitations.

The LFMM will be structured around the following elements:

1) Aggregations of refineries based on geographical proximity (regional definitions) and a measure of refinery complexity (restricting the type of crude oil that can be processed and the product slate)
2) Characterizations (and aggregations) of refinery processes and alternative technology associated with non-petroleum feedstock (e.g., CTL, corn-based ethanol, etc.)
3) Limited crude assays associated with broad sets of crude source/supplies and associated price differentials
4) Simplified product and crude oil import supply curves
5) Tight links with the transportation sector via product prices (and price differentials) to establish the demand for various liquid fuel demands.

The way the LFMM will be structured in addressing each of the five elements above directly impacts the uncertainty and limitations of the model results. Each of these structural assumptions introduces both uncertainty and noteworthy limitations to the LFMM projection. For example, the economic and performance characteristics of the various refinery and alternative technologies play a critical role in determining the mix of crude and alternative feed stocks to be consumed by the LFMM. These characterizations are point estimates of the key parameters used to describe the economic and operational performance of these technologies, and therefore do not reflect the range of performance or uncertainty associated with these technologies.

While some of these structural approaches (e.g., regional definitions and aggregations of refineries) will be tested with the prototype modeling, the LFMM will still be a simplified model of this sector and limited in its completeness. When projecting to 2035 with a model as aggregate as NEMS, it is inappropriate to introduce additional complexity and detail to the model. The more detail that is added, the harder it is to project it out into the next 25 years.

9. Conclusions

The current version of the PMM has shortcomings due to its complexity. The model is difficult to manage, yields over-optimized solutions with questionable results, and has difficulty producing reasonable and robust projections of credible fuel consumption and crude product import balances.

The primary purpose of the LFMM is to project petroleum product, crude oil, and product import prices along with domestic refinery, blending, and product transport operations. In addition, the LFMM will be tasked with providing a complete energy balance between energy inputs and outputs in the refinery process, energy losses, and carbon dioxide emissions resulting from the refinery operations. The LFMM will provide the capability, either within NEMS, or as a standalone refinery modeling system, to simulate aggregate refining operations and quantify impacts of policies on prices, refinery margins, investments, and crude and product imports.

The model must be designed with sufficient policy levers to allow a broad range of policy analysis related to the liquid fuels market. Analytical options would include:

- Analysis of policies related to the introduction of new technologies and/or fuels
- Expansion of biofuels production and technology representation and incorporation of biofuels into the liquid fuels market
- Carbon control, environmental policies (e.g. cap and trade and MARPOL), or other tax credit policies, including mandates (such as Renewable Fuels Standard)
- Option to run and analyze a Low carbon Fuel Standard (LCFS), patterned after California LCSF, at the Census Division or national level

The development of the LFMM includes the following recommendations:

- Include regional detail that is greater than what is offered in the PMM, including a break-out of California in PADD V to address that State's fuel specific regulations.
- Move the responsibility for natural gas liquids to the NEMS natural gas supply or distribution model.
- Select a user-friendly modeling platform like the General Algebraic Modeling System (GAMS) for modeling.
- Update the international component to reflect the interaction between the demand for heavy versus light crudes in the United States and the light/heavy oil price differential.
- Update the alternative fuels representation to include a better competitive technology algorithm.

- Establish the number of refinery types to be used, or develop one unified refinery model.
- Establish the number of product categories to be used.

It is important to develop the LFMM to be robust to the different parameters, so that different modeling approaches can be tested effectively. In addition, there is need to have the LFMM integrated with NEMS as well as a need for its use as a standalone tool to perform studies. It is hoped that the prototype model proposed in this document will be a fruitful first step in achieving the LFMM goals.

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11. Appendix

LFMM Input and Output Requirements

This chapter is divided into three parts. The first section lists the proposed inputs to the LFMM from other NEMS modules, and the proposed outputs from the LFMM to other NEMS modules. The second section details the exogenous inputs that will be required by the LFMM. The third section discusses the key reports required for validation, calibration and benchmarking.

Boundaries of the LFMM – Inputs and Outputs to Other Modules

This section lists the current input and output arrays that describe the proposed interface between the LFMM and the rest of the NEMS modules. The inputs to the LFMM will include the demands for liquid fuels from the demand modules, primarily the transportation module. The Coal Market Module will provide coal price estimates for consumption of coal at refineries and other liquid fuel producers. In addition, the coal supply module will provide coal supply curves and transshipment information needed to allow for coal-to-liquids producers to compete for existing coal supplies. The Oil and Gas Supply Module (OGSM) will provide estimates of the available domestic supply of crude oil. This module will also provide estimates of the natural gas liquids supply available to the gas processing plants or for the gas-to-liquid production. The Natural Gas Transmission and Distribution Module (NGTDM) will provide the natural gas prices needed to support natural gas as a fuel in the refineries or in other liquid fuel production. The Electricity Market Module will provide prices for the electricity consumed by refineries and other liquid fuel producers. In addition this module will provide a price to pay for electricity sold to the grid either from co-generators or as a byproduct to other liquid fuel producers. Biomass supply curves will be provided by the renewable modules so that the liquid fuel producers can effectively compete with other biomass consumers. The world model will provide the cost of imported crude. The NEMS Macroeconomic Activity Module will provide financial parameters for determining investment costs.

In return the LFMM will provide liquid fuel prices for the demand modules and demands for coal, natural gas, electricity, biomass and crude oil to the supply and conversion modules. In the table below are the current NEMS arrays that will be used to pass information between the LFMM and other NEMS modules.

Table 11.1 lists the NEMS arrays that communicate liquid fuel demands from other NEMS modules to and the LFMM.

Table 11.1: LFMM Inputs - Demand Variables

LFMM Input Demand Variables		
NAME	**UNITS**	**DEFINITION**
QMGCM(MNUMCR,MJUMPYR)	Tril Btu/Yr	Motor Gasoline, Commercial
QMGTR(MNUMCR,MJUMPYR)	Tril Btu/Yr	Motor Gasoline, Transportation
QMGIN(MNUMCR,MJUMPYR)	Tril Btu/Yr	Motor Gasoline, Industrial
QMGAS(MNUMCR,MJUMPYR)	Tril Btu/Yr	Motor Gasoline, All Sectors
QJFTR(MNUMCR,MJUMPYR)	Tril Btu/Yr	Jet Fuel, Transportation
QDSRS(MNUMCR,MJUMPYR)	Tril Btu/Yr	Distillate, Residential
QDSCM(MNUMCR,MJUMPYR)	Tril Btu/Yr	Distillate, Commercial
QDSTR(MNUMCR,MJUMPYR)	Tril Btu/Yr	Distillate, Transportation
QDSIN(MNUMCR,MJUMPYR)	Tril Btu/Yr	Distillate, Industrial
QDSEL(MNUMCR,MJUMPYR)	Tril Btu/Yr	Distillate, Electricity (+petroleum coke)
QDSAS(MNUMCR,MJUMPYR)	Tril Btu/Yr	Distillate, All Sectors
QKSRS(MNUMCR,MJUMPYR)	Tril Btu/Yr	Kerosene, Residential
QKSCM(MNUMCR,MJUMPYR)	Tril Btu/Yr	Kerosene, Commercial
QKSIN(MNUMCR,MJUMPYR)	Tril Btu/Yr	Kerosene, Industrial
QKSAS(MNUMCR,MJUMPYR)	Tril Btu/Yr	Kerosene, All Sectors
QLGRS(MNUMCR,MJUMPYR)	Tril Btu/Yr	Liquid Petroleum Gases, Residential
QLGCM(MNUMCR,MJUMPYR)	Tril Btu/Yr	Liquid Petroleum Gases, Commercial
QLGTR(MNUMCR,MJUMPYR)	Tril Btu/Yr	Liquid Petroleum Gases, Transportation
QLGIN(MNUMCR,MJUMPYR)	Tril Btu/Yr	Liquid Petroleum Gases, Industrial
QLGAS(MNUMCR,MJUMPYR)	Tril Btu/Yr	Liquid Petroleum Gases, All Sectors
QRLEL(MNUMCR,MJUMPYR)	Tril Btu/Yr	Residual Fuel, Low Sulfur, Electricity
QRLAS(MNUMCR,MJUMPYR)	Tril Btu/Yr	Residual Fuel, Low Sulfur, All Sectors
QRHEL(MNUMCR,MJUMPYR)	Tril Btu/Yr	Residual Fuel, High Sulfur, Electricity
QRHAS(MNUMCR,MJUMPYR)	Tril Btu/Yr	Residual Fuel, High Sulfur, All Sectors
QRSCM(MNUMCR,MJUMPYR)	Tril Btu/Yr	Residual Fuel, Commercial
QRSTR(MNUMCR,MJUMPYR)	Tril Btu/Yr	Residual Fuel, Transportation
QRSIN(MNUMCR,MJUMPYR)	Tril Btu/Yr	Residual Fuel, Industrial
QRSEL(MNUMCR,MJUMPYR)	Tril Btu/Yr	Residual Fuel, Electricity
QPFIN(MNUMCR,MJUMPYR)	Tril Btu/Yr	Petrochemical Feedstocks, Industrial
QSGIN(MNUMCR,MJUMPYR)	Tril Btu/Yr	Still Gas, Industrial
QPCIN(MNUMCR,MJUMPYR)	Tril Btu/Yr	Petroleum Coke, Industrial
QPCEL(MNUMCR,MJUMPYR)	Tril Btu/Yr	Petroleum Coke, Electricity
QPCAS(MNUMCR,MJUMPYR)	Tril Btu/Yr	Petroleum Coke, All Sectors
QASIN(MNUMCR,MJUMPYR)	Tril Btu/Yr	Asphalt and Road Oil, Industrial
QOTTR(MNUMCR,MJUMPYR)	Tril Btu/Yr	Other Petroleum Transp., (lubes, aviation gas)
QOTIN(MNUMCR,MJUMPYR)	Tril Btu/Yr	Other Petroleum, Industrial
QOTAS(MNUMCR,MJUMPYR)	Tril Btu/Yr	Other Petroleum, All Sectors
QMETR(MNUMCR,MJUMPYR)	Tril Btu/Yr	Methanol Transportation
QETTR(MNUMCR,MJUMPYR)	Tril Btu/Yr	Ethanol Transportation
INQLGPF(MNUMCR,MNUMYR)	Tril Btu/Yr	Consumption of LPG feedstocks

Table 11.2 describes the supply of domestic crude from the OGSM to the LFMM.

Table 11.2: LFMM Inputs - Domestic Crude Supplies

LFMM Input Domestic Crude Availability		
NAME	**UNITS**	**DEFINITION**
RFQTDCRD(MNUMOR+2,MJUMPYR)	Mbbl/cd	Domestic Crude Production

Table 11.3 describes the information from the International Energy Module needed to create the global supply curve for crude and the incremental supply curves by crude type.

Table 11.3: LFMM Inputs - Imported Crude Prices and Quantities

LFMM Input Global Crude Availability		
NAME	**UNITS**	**DEFINITION**
CRUDEPOINTS(MNUMYR,9,2)	Mbbl/cd	Global Crude Supply Curve
IT_WOP(MJUMPYR,2)	$87/bbl	World oil price (2--units)
Q_ITIMCRSC(MJUMPYR,5,5,3)	Mbbl/cd	Crude import supply curve quant.
P_ITIMCRSC(MJUMPYR,5,5,3)	$87/bbl	Crude import supply curve prices

Table 11.4 describes the Alaskan NGL production from OGSM and domestic dry gas production from the NGTDM to support the GTL production in Alaska.

Table 11.4: LFMM Inputs - Alaskan GTL Production Supplies

LFMM Input Natural Gas Supply Curve for GTL production in Alaska		
NAME	**UNITS**	**DEFINITION**
OGNGLAK(MJUMPYR)	Mbbl/cd	NGL from Alaska
OGPRDNG(MNUMOR,MJUMPYR)	Bcf/Yr	Domestic dry gas production (W/L&P)

Table 11.5 describes the coal supply and transport information from the Coal Market Module (CMM) required to establish coal supply for the coal-to-liquids production. EMELPSO2, EMEL_PHG and JCLCLNR are from the Emissions Policy Submodule (EPM) and provide the associated emissions fees for determining the delivered cost of coal to CTL units.

Table 11.5: LFMM Inputs - Coal Supply Curves for CTL Production

LFMM Input Coal Supply Curve for Coal-to-Liquids Production		
NAME	**UNITS**	**DEFINITION**
EMM_MEF(NSTEP,NRANK,NCLUT1)	factor	Mercury Emission Factor by Plant Type, Coal Rank and Activated Carbon Step(1=>No ACI)
PLNT_EMF(ECP$CAP,NRANK)	factor	Emission Modification Factor by Plant Type and Coal Rank

LFMM Input Coal Supply Curve for Coal-to-Liquids Production		
NAME	**UNITS**	**DEFINITION**
RCLCLNR(NDRGG,MNUMYR,NCLUT1)	percent	Combined Percent Removal by ECP Plant Type
EMELPSO2(MNUMYR,MX_SO2_GRP)	87$/MMBtu	Sulfur Dioxide Allowance Price
EMEL_PHG(MX_HG_GRP,MNUMYR)	87$/MMBtu	Mercury Allowance Price
JCLCLNR(MNUMYR,NCLPR2)	87$/MMBtu	Carbon Price by Coal Demand Sector
SO2_SHR_BY_CLRG(NDREG,MX_SO2_GRP)	factor	Share of SO2 Emission in SO2 Group by Coal Region
CTL_OTHER(MX_NCOALS,MNUMYR)	TrilBTU/yr	Expected non-CTL coal demand
CTL_CDSL1(NDREG,MNUMPR)	fraction	Maps coal demand regions to refinery PADDs as fraction of total into PADD
CTL_CLDR(NDREG)	flag: 0,1	Does the coal demand region have CTL demand? ('0' means 'no'; '1' means 'yes')
EFD_RANK(MX_NCOALS+MX_ISCV)	flag	EFD Coal Rank Indicator (0 - 4)
CTL_TRATE(MX_NCOALS,NDREG)	87$/MMBtu	Coal transportation rates for Coal-to-Liquids
CTL_TYPE(MX_NCOALS)	None	CTL coal type by supply curve
XCL_1TESC(MX_NCOALS,0:ECP$FPH, MNUMYR,NDREG)	fraction	Coal transportation rate multipliers
XCL_BTU(MX_NCOALS + MX_ISCV)	MMBtu/ton	Average heat content by supply curve
XCL_CAR(MX_NCOALS + MX_ISCV)	lbs CO2/MMBtu	Average CO2 emissions factor of coal by supply curve
XCL_HG(MX_NCOALS + MX_ISCV)	lbs Hg/trilBtu	Average mercury content of coal by supply curve
XCL_PCAP(MX_NCOALS,MNUMYR)	trilBTU/yr	Current year coal mine capacity by supply curve
XCL_MX_PCAP(MX_NCOALS)	fraction	Maximum allowable increase in coal mine productive capacity by supply curve for current year
XCL_QECP(MX_NCOALS,0:ECP$FPH,MNUMYR)	trilBTU	Coal supply quantities by supply curve step
XCL_PECP(MX_NCOALS,11,0:ECP$FPH,MNUMYR)	87$/MMBtu	Coal supply prices by step - lower to upper
XCL_STEPS(11)	factor	Coal supply curve step size
XCL_SO2(MX_NCOALS + MX_ISCV)	lbs SO2/MMBtu	Average SO2 content of coal by supply curve
LCVBTU(MNUMPR,MJUMPYR)	MMbtu/ton	CTL coal supply curve heat content
LTRNTON(MNUMPR,MJUMPYR)	$87/ton	Coal transportation rate to CTL facility
L_SO2P(MNUMPR,MNUMYR)	$87/MMBtu coal	Incremental cost of coal due to SO2 allowance price
L_HGP(MNUMPR,MNUMYR)	$87/MMBtu coal	Incremental cost of coal due to Hg allowance price

Table 11.6 describes the LFMM input from the Renewables Module needed to create biomass supply curves for cellulosic ethanol production and biomass to liquids production.

Table 11.6: LFMM Inputs - Biomass Supply Curves for Ethanol and BTL Production

LFMM Input Biomass Supply Curve for Cellulosic Ethanol and Biomass to Liquids Production		
NAME	**UNITS**	**DEFINITION**
NM_BM_SUP_STP	None	Number of Biomass Supply Steps
WDSUP_Q_UM(NWDSUPQ,NDREG,MNUMYR+ECP$FPH)	trilBtu/yr	Urban Wood Waste Biomass Supply Quantities
WDSUP_P_UM(NWDSUPQ,MNUMYR+ECP$FPH)	87$/MMBtu	Urban Wood Waste Biomass Supply Prices
WDSUP_Q_FR(NWDSUPQ,NDREG,MNUMYR+ECP$FPH)	trilBtu/yr	Forest Residue Biomass Supply Quantities
WDSUP_P_FR(NWDSUPQ,MNUMYR+ECP$FPH)	87$/MMBtu	Forest Residue Biomass Supply Prices
WDSUP_Q_AG(NWDSUPQ,NDREG,MNUMYR+ECP$FPH)	trilBtu/yr	Agricultural Residue Biomass Supply Quantities
WDSUP_P_AG(NWDSUPQ,MNUMYR+ECP$FPH)	87$/MMBtu	Agricultural Residue Biomass Supply Prices
WDSUP_Q_EC(NWDSUPQ,NDREG,MNUMYR+ECP$FPH)	trilBtu/yr	Energy Crops Biomass Supply Quantities
WDSUP_P_EC(NWDSUPQ,MNUMYR+ECP$FPH)	87$/MMBtu	Energy Crops Biomass Supply Prices
WDSUP_AVL(MNUMFS)	None	Logical Variable to Indicate Whether Selected Biomass Supply Curves are Available
BM_TYP_CD(MNUMFS)	None	Two Digit Alphanumeric Code Representing the type of Biomass Feedstock
MAP_CD_TO_CL(NDREG,MNUMCR)	None	Map Census Regions to Coal Demand / Biomass Supply Regions
MP_BM_ET(MNUMFS)	None	For Cellulosic Ethanol Production identify supply types used
MP_BM_BT(MNUMFS)	None	For Biomass-to-Liquids Production identify supply types used
QBMRSCL(0:MNUMFS,0:NDREG,MNUMYR+ECP$FPH)	trilBtu/yr	Residential Demand for Biomass used from the supply curves
MP_BM_RS(MNUMFS)	None	For Residential Demand identify supply types used, if any
QBMCMCL(0:MNUMFS,0:NDREG,MNUMYR+ECP$FPH)	trilBtu/yr	Commercial Demand for Biomass used from the supply curves
MP_BM_CM(MNUMFS)	None	For Commercial Demand identify supply types used, if any
QBMINCL(0:MNUMFS,0:NDREG,MNUMYR+ECP$FPH)	trilBtu/yr	Industrial Demand for Biomass used from the supply curves
MP_BM_IN(MNUMFS)	None	For Industrial Demand identify supply types used, if any
QBMH2CL(0:MNUMFS,0:NDREG,MNUMYR+ECP$FPH)	trilBtu/yr	Hydrogen Production Demand for Biomass used from the supply curves
MP_BM_H2(MNUMFS)	None	For Hydrogen Production Demand identify supply types used, if any
QBMPWCL(0:MNUMFS,0:NDREG,MNUMYR+ECP$FPH)	trilBtu/yr	Electric Power Production Demand for Biomass used from the supply curves

LFMM Input Biomass Supply Curve for Cellulosic Ethanol and Biomass to Liquids Production		
NAME	**UNITS**	**DEFINITION**
MP_BM_PW(MNUMFS)	None	For Electric Power Production Demand identify supply types used

Table 11.7 describes the natural gas price from NGTDM and the coal price from the CMM that are used to determine fuel consumption in both refineries and other liquid fuel production facilities.

Table 11.7: LFMM Inputs - Natural Gas and Coal Prices

LFMM Input Natural Gas and Coal Prices		
NAME	**UNITS**	**DEFINITION**
PNGIN(MNUMCR,MJUMPYR)	$87/MMBtu	Natural gas, industrial
PGIIN(MNUMCR,MJUMPYR)	$87/MMBtu	Noncore industrial sector prices
PCLIN(MNUMCR,MJUMPYR)	$87/ton	Coal, industrial prices

Table 11.8 describes the electricity inputs from the EMM. The EWSPRCN array is used to value the electricity produced by combined heat and power plants, electricity produced as a co-product of coal-to-liquids and biomass-to-liquids production facilities. The PELIN array is used as the price of electricity to refineries and other liquid fuel production facilities. The TRCTLFCF and TRCTLOVR provide investment cost information for connecting CTL units to the electric grid.

Table 11.8: LFMM Inputs - Electricity Prices

LFMM Input Electricity Prices		
NAME	**UNITS**	**DEFINITION**
EWSPRCN(MNUMNR,MNUMYR)	$87/MMBtu	Average wholesale price (time wtd energy + reliab)
PELIN(MNUMCR,MJUMPYR)	$87/MMBtu	Purchased electricity, industrial
TRCTLFCF(MNUMNR)	fraction	Transmission FCF, stored for CTL decision in PMM
TRCTLOVR(MNUMNR)	87$/kW	Transmission overnight cost, stored for CTL decision

Table 11.9 describes the carbon prices for natural gas and coal.

Table 11.9: LFMM Inputs - Carbon Prices

LFMM Input Carbon Costs		
NAME	**UNITS**	**DEFINITION**
JGIIN(MJUMPYR)	$87/MMBtu	NG Prices w/ emissions penalty, industrial
JCLIN(MJUMPYR)	$87/MMBtu	Coal Prices w/ emissions penalty, industrial

Table 11.10 describes the economic variables from the Macroeconomic Model to be used by the LFMM.

Table 11.10: LFMM Inputs - Economic Variables

LFMM Input Economic Variables		
NAME	**UNITS**	**DEFINITION**
MC_PJGDP(-2:MJUMPYR)	Index	chained price index- gross domestic product; 1987=1.0
MC_RMCORPBAA(MJUMPYR)	Percent	Industrial Baa Bond rate
MC_RMTCM10Y(MJUMPYR)	Percent	10 year treasury note yield; percent per year, average of daily rates
MC_NP(MNUMCR,MNUMYR)	Millions	Total Population
MC_WPISOP3200(MNUMYR)	Index	Producer Price Index; 1982=1.0

Table 11.11 describes other emissions variables used to model carbon initiatives.

Table 11.11: LFMM Inputs - Other Emission Variables

LFMM Input Other Emission Variables		
NAME	**UNITS**	**DEFINITION**
EMCMC(MNUMCR,MNPOLLUT,MJUMPYR)	M tons/yr	Emissions by Region, commercial
EMELC(MNUMCR,MNPOLLUT,MJUMPYR)	M tons/yr	Emissions by Region, electric utility
EMETAX(15,MJUMPYR)	$87/ton	Excise (Consumption) Tax by Fuel
EMINCN(MNUMCR,MNPOLLUT,MJUMPYR)	M tons/yr	Non-comb emissions by region, industrial
EMNT(MNUMCR,MNPOLLUT,MJUMPYR)	M tons/yr	NGTDM Emissions by Region
EMPMCC(MNUMCR,MNPOLLUT,MJUMPYR)	M tons/yr	PMM Emissions by Region- Combined
EMPMCN(MNUMCR,MNPOLLUT,MJUMPYR)	M tons/yr	PMM Emissions by Region-Noncombined
EMRSC(MNUMCR,MNPOLLUT,MJUMPYR)	M tons/yr	Residential Emissions by Region
EMTRC(MNUMCR,MNPOLLUT,MJUMPYR)	M tons/yr	Trans Emissions by Region
NUM_SO2_GRP	number	Number of SO2 Compliance Groups

Table 11.12 lists the outputs required by other NEMS modules. Specifically, this table describes the liquid fuel prices that will be determined by the LFMM.

Table 11.12: LFMM Outputs - Liquid Fuel Prices

LFMM Outputs to Other NEMS Modules Liquid Fuel Prices		
NAME	**UNITS**	**DEFINITION**
PASIN(MNUMCR,MJUMPYR)	$87/MMBtu	Asphalt, Road Oil, Industrial
PDSAS(MNUMCR,MJUMPYR)	$87/MMBtu	Distillate, All Sectors
PDSCM(MNUMCR,MJUMPYR)	$87/MMBtu	Distillate, Commercial
PDSEL(MNUMCR,MJUMPYR)	$87/MMBtu	Distillate, Electricity (+petroleum coke)
PDSIN(MNUMCR,MJUMPYR)	$87/MMBtu	Distillate, Industrial
PDSRS(MNUMCR,MJUMPYR)	$87/MMBtu	Distillate, Residential
PDSTR(MNUMCR,MJUMPYR)	$87/MMBtu	Distillate, Transportation
PETTR(MNUMCR,MJUMPYR)	$87/MMBtu	Ethanol, Transportation
PJFTR(MNUMCR,MJUMPYR)	$87/MMBtu	Jet Fuel, Transportation
PKSAS(MNUMCR,MJUMPYR)	$87/MMBtu	Kerosene, All Sectors
PKSCM(MNUMCR,MJUMPYR)	$87/MMBtu	Kerosene, Commercial
PKSIN(MNUMCR,MJUMPYR)	$87/MMBtu	Kerosene, Industrial
PKSRS(MNUMCR,MJUMPYR)	$87/MMBtu	Kerosene, Residential
PLGAS(MNUMCR,MJUMPYR)	$87/MMBtu	Liquid Petroleum Gases, All Sectors
PLGCM(MNUMCR,MJUMPYR)	$87/MMBtu	Liquid Petroleum Gases, Commercial
PLGIN(MNUMCR,MJUMPYR)	$87/MMBtu	Liquid Petroleum Gases, Industrial
PLGINPF(MNUMCR,MNUMYR)	$87/MMBtu	Industrial LPG feedstock
PLGRS(MNUMCR,MJUMPYR)	$87/MMBtu	Liquid Petroleum Gases, Residential
PLGTR(MNUMCR,MJUMPYR)	$87/MMBtu	Liquid Petroleum Gases, Transportation
PMETR(MNUMCR,MJUMPYR)	$87/MMBtu	Methanol, Transportation
PMGAS(MNUMCR,MJUMPYR)	$87/MMBtu	Motor Gasoline, All Sectors
PMGCM(MNUMCR,MJUMPYR)	$87/MMBtu	Motor Gasoline, Commercial
PMGIN(MNUMCR,MJUMPYR)	$87/MMBtu	Motor Gasoline, Industrial
PMGTR(MNUMCR,MJUMPYR)	$87/MMBtu	Motor Gasoline, Transportation
POTAS(MNUMCR,MJUMPYR)	$87/MMBtu	Other Petroleum, All Sectors
POTIN(MNUMCR,MJUMPYR)	$87/MMBtu	Other Petroleum, Industrial
POTTR(MNUMCR,MJUMPYR)	$87/MMBtu	Other Petroleum, Transportation
PPFIN(MNUMCR,MJUMPYR)	$87/MMBtu	Petrochemical Feedstocks, Industrial
PRHAS(MNUMCR,MJUMPYR)	$87/MMBtu	Residual Fuel, High Sulfur, All Sectors
PRHEL(MNUMCR,MJUMPYR)	$87/MMBtu	Residual Fuel, High Sulfur, Electricity
PRHTR(MNUMCR,MJUMPYR)	$87/MMBtu	Residual Fuel, High Sulfur, Transportation
PRLAS(MNUMCR,MJUMPYR)	$87/MMBtu	Residual Fuel, Low Sulfur, All Sectors
PRLCM(MNUMCR,MJUMPYR)	$87/MMBtu	Residual Fuel, Low Sulfur, Commercial
PRLEL(MNUMCR,MJUMPYR)	$87/MMBtu	Residual Fuel, Low Sulfur, Electricity
PRLIN(MNUMCR,MJUMPYR)	$87/MMBtu	Residual Fuel, Low Sulfur, Industrial
PRLTR(MNUMCR,MJUMPYR)	$87/MMBtu	Resid. Fuel, Low Sulfur, Transportation

Table 11.13 describes the arrays that pass fuel demands for refinery and other liquid fuel production to the appropriate NEMS modules.

Table 11.13: LFMM Output to Other NEMS Modules – Fuel and Feedstock Consumption

LFMM Output to Other NEMS Modules – Fuel and Feedstock Consumption		
NAME	**UNITS**	**DEFINITION**
QCLRF(MNUMCR,MJUMPYR)	Tril Btu/Yr	Purchased Coal, Refinery
QELRF(MNUMCR,MJUMPYR)	Tril Btu/Yr	Purchased Electricity, Refinery
QNGRF(MNUMCR,MJUMPYR)	Tril Btu/Yr	Natural Gas, Refinery
QBMETCL(0:MNUMFS,0:NDREG,MNUMYR+ECP$FPH)	trilBtu/yr	Ethanol Production Demand for Biomass used from the supply curves
QBMBTCL(0:MNUMFS,0:NDREG,MNUMYR+ECP$FPH)	trilBtu/yr	BTL Production Demand for Biomass used from the supply curves
QBMRFBTL(MNUMCR,MNUMYR)	TrilBTU/yr	Quantity of biomass for BTL
QCLRFPD(MNUMPR,MNUMYR)	Tril BTU/yr	Quantity of coal for CTL
QMERF(MNUMCR,MNUMYR)	Tril BTU/yr	Quantity of methanol purchased by refineries
AKGTLPRD(MNUMYR)	Mbbl/cd	GTL produced in Alaska
AKGTL_NGCNS(MNUMYR)	BCF	Natural gas consumed in GTL process
BTLFRAC(4, MNUMPR,MNUMYR)	MMbbl/cd	Quantity of BTL liquid produced by type
CTLFRAC(4, MNUMPR,MNUMYR)	MMbbl/cd	Quantity of CTL liquid produced by type
CBTLFRAC(2,4,MNUMPR,MNUMYR)	MMbbl/cd	Liquids produced from coal/biomass combo plant (1 if by coal, 2 if by biomass)
GLBCRDDMD(MNUMYR)	Mbbl/cd	World crude oil demand (PMM results)
QCLETH(MJUMPYR,MNUMCR)	TrilBtu/yr	Coal total, Ethanol plants
QELETH(MJUMPYR,MNUMCR)	TrilBtu/yr	Purchased Electricity total, Ethanol plants
QNGETH(MJUMPYR,MNUMCR)	TrilBtu/yr	Natural gas total, Ethanol plants
QBMET(MNUMCR,MNUMYR,NUMETHQ),4	Mbbl/cd	Biomass Ethanol quantity
PDSTRHWY(MNUMCR,MJUMPYR)	$87/MMBtu	On-road distillate price, transportation sector
QDSTRHWY(MNUMCR,MJUMPYR)	tril Btu/yr	On-road distillate quantity, transportation sector
CFDSTRHWY(MJUMPYR)	MMBtu/bbl	On-road distillate conversion factor, trans. sector
CGREGEN(MNUMCR,MJUMPYR,5,2)	GWh	Refinery CHP Generation

Exogenous Inputs to the LFMM

LFMM modeling must start with a snapshot of the current liquid fuel conversion and production units. As the LFMM has been defined to include off-shore operations that have and can be expected to continue being major suppliers of liquids to the domestic markets, the description of these facilities must also be included in the initial inventory. Examples of these units would be the refineries in the Virgin Islands and the Canadian Maritime Provinces that produce petroleum products for the East Coast markets. The inventory of existing equipment must include a relatively detailed description that includes feedstock requirements, fuel consumption needs, as well as fixed and variable operating costs for each production facility and conversion unit. To the extent that these units can be used in more than one operating mode, this information is needed for each of the alternatives.

For each liquid fuel, information is needed to describe the quality specifications that must be achieved. Some of these specifications describe the properties needed to be useful as a fuel. Other specifications are legislated so that the fuel's impact on the environment is within acceptable ranges. In combination with the physical description of the available units, these specifications limit which feedstock can be used and which conversion units must be used to produce a slate of products that can be sold to satisfy all the demands for liquid fuels.

This list of data requirements must also include the investment requirements to add new units or facilities to the existing stock of equipment. These new facilities will include not only conventional refinery units but also bio-fuel production facilities for which cost and performance data can only be estimated. Quantifiable assumptions about the speed at which these new technologies can be introduced into the liquid fuels market will be needed to insure reasonable penetration rates.

The LFMM must capture the existing liquid fuel transport infrastructure so that limits can be placed on the flows, and costs can be quantified. These costs will be included in the delivered costs of fuels. In addition, the investment requirements to expand the existing transportation infrastructure are also necessary. This includes expanding the transport infrastructure to include transport for new alternative fuels as needed. Some alternative products can be blended with conventional petroleum products – and use existing transport modes. For example, the Fischer-Tropsch liquids produced from coal or biomass can be directly mixed with the similar petroleum products they replace. On the other hand, some alternative fuels like ethanol must be transported separately and only blended into the final products during distribution.

As noted above, the LFMM will endogenize some of the international liquid fuels market, which has historically been a major supplier of product to the domestic markets. In addition, the International Energy Module will provide information about the availability of global crude oil supplies. However, additional information will be needed about expectations of other imports and/or exports of liquid fuel products or feedstocks. This need is not only for information on petroleum products but also on alternative fuels such as ethanol production from Latin America. Additional information will also be needed on the expected quality of imported crude oil and other petroleum feedstocks.

The LFMM will produce wholesale liquid fuel prices as the output of its examination of the alternatives available for producing a slate of liquid fuels ready for distribution to the end users. In order to produce final prices, distribution costs and excise taxes must be provided. Although taxes are largely known, blending State taxes to regional levels requires some finesse. For conventional products, the remainder of the distribution cost can be quantified as the difference between the wholesale price and the end use price, minus taxes. For emerging products like E85, however, additional information will be needed to quantify the cost of building the required distribution infrastructure.

Finally, environmental information is needed, not only for the fuel consumed by the conversion processes but for the products produced. Current and proposed legislation will limit the emissions of pollutants, including sulfur, toxics such as mercury, and greenhouse gases such as carbon dioxide. To model this legislation, the environmental quality of the fuels and feedstocks into the LFMM must be known. The environmental impact of the conversion processes and the subsequent quality of the liquids fuels produced must also be known. Some of this information will be available from other NEMS modules, as noted in the section above, but it is expected that this information will need to be supplemented exogenously.

LFMM Output for Reporting

Table 11.14 describes the additional output variables needed to support the existing NEMS reports.

Table 11.14: Other LFMM Outputs

Other LFMM Output Arrays		
NAME	**UNITS**	**DEFINITION**
ADVCAPCD(MNUMCR,MNUMYR)	Mbbl/cd	Advanced Ethanol Plant Capacity
BANKUSED(MNUMYR)	billion credits	Number of banked credits used
BANKCRED(MNUMYR)	billion credits	Number of credits in the bank
BLDPRD(MNUMPR,MNUMYR)	MMbbl/cd	Product blending components input to refinery
BLDREFINC(MNUMPR,MNUMYR)	MMbbl/cd	Conventional gasoline blending components
BLDREFINR(MNUMPR,MNUMYR)	MMbbl/cd	Reformulated gasoline blending components
BTUTOTAL(MNUMYR)	Mt C per trill Btu	Total BTUs in all transportation fuels
CARBOFFSET(MNUMYR)	Mt C per year	Amount of C from petroleum that must be offset by biofuels
CARBTOTAL(MNUMYR)	Mt C per year	Total C in all transportation fuels
CBIODUAL(MNUMYR)	$87/tonne	Price from biofuels offset row (CTRNBIO)
CPERBTU(MNUMYR)	Mt C per trill Btu	C per unit energy for transportation fuels
CELLCD(MNUMCR,MNUMYR)	Trill Btu/yr	Cellulose used for ethanol and BTL
CELLIMPFRAC(MNUMCR,MNUMYR)	fraction	Fraction of ethanol imports that is cellulosic
CLLCAPCD(MNUMCR,MNUMYR)	Mbbl/cd	Cellulosic Ethanol Plant Capacity
CONEFF(MNUMYR)	gal/ton	Gallon Ethanol per short ton Cellulose
CRNCAPCD(MNUMCR,MNUMYR)	Mbbl/cd	Corn Ethanol Plant Capacity
DDGSFEED(MNUMCR,MNUMYR)	tons	DDGS sold as feed
DDGSFUEL(MNUMCR,MNUMYR)	tons	DDGS sold/used as fuel
DDGSPRICE(MNUMCR,MNUMYR)	$87/s-ton	DDGS (Dried distilled grain with solubles) price
DSMURS(MNUMCR,MNUMYR,2)	$87/bbl	Residential Distillate Markups
DSMUTR(MNUMCR,MNUMYR,2)	$87/bbl	Tran Distillate Markups
ETHCREDIT(MNUMYR)	$87/bbl	Ethanol credit price
ETHCREDITZ(MNUMYR)	Mbbl/day	Distress ethanol credits
ETHVOL(MNUMYR)	Fraction	RFS constraint of total pool (fraction)
GAINPCT(MNUMPR,MNUMYR)	Fraction	Gain as percent
GRD2DSQTYCD(MNUMCR,MNUMYR)	Mbbl/cd	Quantity of green diesel to distillate

Other LFMM Output Arrays		
NAME	**UNITS**	**DEFINITION**
GRNCAPCD	Mbbl/cd	Non-corn, non-adv ethanol plant capacity
GRNCD(MNUMCR,MNUMYR)	MM bushels/yr	Grain consumption by CD
GRN2MGQTYCD(MNUMCR,MNUMYR)	Mbbl/cd	Quantity of green naphtha to motor gasoline
JFMUTR(MNUMCR,MNUYR,2)	$87/bbl	Transportation Jet Fuel Markups
LCFSSAFE(MNUMYR)	Mt carbon	Safety valve for biofuels carbon constraint
MGMUTR(MNUMCR,MNUMYR,2)	$87/bbl	Transportation Gasoline Markups
MINREN(MNUMYR)	Mbbl/cd	Minimum renewable in gasoline and diesel
MX_IPMM_D_REG	4	Maximum number of int'l demand regions
MX_IPMM_D_STP	20	Maximum number of int'l demand steps
MX_IPMM_D_PRD	18	Maximum number of int'l demand products
MX_IPMM_D_AGR	5	(not used)
MX_IPMM_D_PRM	10	Maximum number of int'l demand projection parameters
MX_IPMM_C_REG	1	Maximum number of int'l crude supply regions
MX_IPMM_C_STP	9	Maximum number of int'l crude supply steps
MX_IPMM_C_TYP	5	Maximum number of int'l crude types
MX_IPMM_R_REG	4	Maximum number of int'l refinery regions
MX_IPMM_R_TYP	2	Maximum number of int'l refinery types
MX_IPMM_R_PRD	18	Maximum number of int'l refinery products
MX_IPMM_R_OPR	5	Maximum number of int'l refinery operating modes
MX_IPMM_T_MOD	10	Maximum number of int'l transportation modes
NGLRF(MNUMPR,MNUMYR,6,2)	MM bbl/cd	Natural gas liquids to refinery
OTHOXY(MNUMPR,MNUMYR)	MM bbl/cd	Oxygenates, hydrogen, and other hydrocarbons
PALBOB(MNUMCR,MNUMYR)	$87/bbl	wholesale gasoline price
PALMG(MNUMCR, MNUMYR)	$87/bbl	Motor gasoline all combined
PDS(MNUMCR, MNUMYR)	$87/bbl	Distillate fuel oil
PDSL(MNUMCR, MNUMYR)	$87/bbl	Low sulfur diesel
PDSU(MNUMCR,MNUMYR)	$87/bbl	Ultra Low Sulfur Diesel
PDSC(MNUMCR,MNUMYR)	87$/MMBtu	AVG PR for DS for COM
PDSI(MNUMCR,MNUMYR)	87$/MMBtu	AVG PR for DS for IND
PDST(MNUMCR,MNUMYR)	87$/MMBtu	AVG PR for DS for TRN
PDSUTR(MNUMCR,MNUMYR)	87$/MMBtu	ULTRA LOW SUL DIESEL, TRN PRICE
PDSLTR(MNUMCR,MNUMYR)	87$/MMBtu	LOW SUL DIESEL, TRN PRICE
PJF(MNUMCR, MNUMYR)	$87/bbl	Jet fuel
PLMQTYCD(MNUMCR,MNUMYR)	Mbbl/cd	Palm Oil Imports
PN2HTR(MNUMCR,MNUMYR)	87$/MMBtu	2370ppm DIESEL, TRN PRICE
PRIORCREDIT(MNUMYR)	billion credits	Prior year credits
PSA_TAB(35,MNUMPR,MNUMYR)	M bbl/cd	Refinery unit capacity from PSA report
QDSUTR(MNUMCR,MNUMYR)	trillBTU/yr	ULTRA LOW SUL DIESEL, TRN QTY
QDSLTR(MNUMCR,MNUMYR)	trillBTU/yr	LOW SUL DIESEL, TRN QTY,
QN2HTR(MNUMCR,MNUMYR)	trillBTU/yr	2370ppm DIESEL, TRN QTY,
QDSUIN(MNUMCR,MNUMYR)	trillBTU/yr	ULTRA LOW SUL DIESEL, IND QTY
QDSLIN(MNUMCR,MNUMYR)	trillBTU/yr	LOW SUL DIESEL, IND QTY
QN2HIN(MNUMCR,MNUMYR)	trillBTU/yr	2370ppm DIESEL, IND QTY
QDSUCM(MNUMCR,MNUMYR)	trillBTU/yr	ULTRA LOW SUL DIESEL, COM QTY

Other LFMM Output Arrays		
NAME	**UNITS**	**DEFINITION**
QDSLCM(MNUMCR,MNUMYR)	trillBTU/yr	LOW SUL DIESEL, COM QTY
QN2HCM(MNUMCR,MNUMYR)	trillBTU/yr	2370ppm DIESEL, COM QTY
RFBTLWH(MNUMYR)	Mbbl/cd	BTL liquid directly to product pool
RFCBTLWH(MNUMYR)	Mbbl/cd	CBTL liquid directly to product pool
RFCTLWH(MNUMYR)	Mbbl/cd	CTL liquid directly to product pool
RFDSTSHD(MNUMPR,MNUMYR)	MMbbl/cd	Refinery idle capacity
RFENVFX(MNUMCR, MNUMYR,20)	$87/bbl	Refinery Environmental Fixed Costs
RFHCXH2IN(MNUMPR,MNUMYR)	MMbbl/cd	H2 from natural gas to refinery
RFIMPEXPEND(MNUMYR)	billion $87/yr	Import Expenditures
RFOXYIN(MNUMPR,MNUMYR)		Oxygenates input to refinery
RFQEL(MNUMYR)	MMbbl/cd	Utility product demand
RFQNGPF(MNUMCR,MNUMYR)	trillBTU/yr	Consumption of natural gas feedstocks to H2
RFQSGPF(MNUMCR,MNUMYR)	trillBTU/yr	Consumption of still gas feedstocks to H2
RFQIN(MNUMYR)	MMbbl/cd	Industrial product demand
RFQRC(MNUMYR)	MMbbl/cd	Residential/Commercial product demand
RFQSECT(MNUMYR)	MMbbl/cd	Total sectoral demand
RFQTR(MNUMYR)	MMbbl/cd	Transportation product demand
RFSG2H2IN(MNUMPR,MNUMYR)	Mbfoe/cd	Still gas input to refinery for hydrogen
SBO_FUEL(MNUMCR,MNUMYR)	MMbbl/cd	Soybean oil consumption for fuel
SBO_PRICE(MNUMCR,MNUMYR)	$87/bbl	Soybean oil price
SBO2GDTPD(MNUMPR,MNUMYR)	Mbbl/cd	SBO to green diesel
SBOQTYCD(MNUMCR,MNUMYR)	Mbbl/cd	SBO oil quantity
TOTCRDIN((MNUMPR,MNUMYR)	MMbbl/cd	Crude oil input to refinery
TOTUFOIN(MNUMPR,MNUMYR)	MMbbl/cd	Unfinished oil input to refinery
UBAVOL(MNUMPR,MNUMYR)	M bbl/cd	Upgraded Bio-oil A volume (biomass pyrolysis)
USPLTRIF(300,MNUMYR)	$87/bbl	U.S. pipeline tariff (300 of them)
WGR_FUEL(MNUMCR,MNUMYR)	Mbbl/cd	Other feedstock (e.g., white grease) consumption for biodiesel
WGR_PRICE(MNUMCR,MNUMYR)	$87/bbl	Price for other feedstock (e.g., white grease) biodiesel
WGR2GDTPD(MNUMPR,MNUMYR)	Mbbl/cd	WGR to green diesel
WS_RBOB(MNUMCR,MNUMYR)	$87/bbl	Wholesale price of mogas
YGR2GDTPD(MNUMPR,MNUMYR)	Mbbl/cd	YGR to green diesel
YGR_FUEL(MNUMCR,MNUMYR)	MMbbl/cd	Yellow grease consumption for fuel
YGR_PRICE(MNUMCR,MNUMYR)	$87/bbl	Yellow grease price
AKGTLEXP(MNUMYR)	Mbbl/cd	GTL exported from Alaska
CRNPRICE(MNUMCR,MNUMYR)	$87/bushel	Price of corn
DCRDWHP(MNUMOR,MNUMYR)	$87/bbl	Domestic crude wellhead price
ETHNE85	Fraction	Percent ethanol in E85
ETHCREDITZ(MNUMYR)	Mbbl/cd	Distress ethanol credits
GTLFRAC(4, MNUMPR,MNUMYR)	MMbbl/cd	Quantity of GTL liquid produced by type
PRDSTKWDR(MNUMPR,MNUMYR)	Mbbl/cd	Product stock withdrawal
QBMRFBTL(MNUMCR,MNUMYR)	TrillBTU/yr	Quantity of biomass for BTL
QCRDRF(MNUMPYR,MNUMYR,6,4)	Mbbl/cd	Quantity of crude input to refinery
RFBTLPRD(MNUMYR)	Mbbl/Day	Quantity of liquids from biomass
RFCTLPRD(MNUMYR)	Mbbl/Day	Quantity of liquids from coal

Other LFMM Output Arrays		
NAME	**UNITS**	**DEFINITION**
RFCBTLPRD(MNUMYR)	Mbbl/Day	Quantity of liquids from coal/biomass combo
RFDCRDP(MNUMOR,MNUMYR,5)	$87/bbl	Domestic crude price by crude type
RFQDCRD(MNUMOR+2,MNUMYR)	MMbbl/yr	Domestic conventional crude
RFQDINPOT(MNUMPR,MNUMYR)	MMbbl/cd	Quantity other input to refinery
RFPQNGL(MNUMPR,MNUMYR,6,2)	$87/bbl,Mbbl/cd	Prc/quan of NGL by PAD district
RFQNGPFCD(MNUMCR,MNUMYR)	Trill BTU/yr	Natural gas to H2 sent to NGTDM module
TRGNE85	Fraction	Percent TRG in E85
RFQPRCG(MNUMPR,MNUMYR)	MMbbl/cd	Quantity of processing gains
RFQPRDT(MNUMCR, MNUMYR)	MMbbl/cd	Total product supplied
RFQTDCRD(MNUMOR+2,MNUMYR)	MMbbl/yr	Total domestic crude
RFSPRFR(MNUMYR)	MMbbl/cd	Rf spr fill rate
RFSPRIM(MNUMYR)	MMbbl/cd	Spr imports
XDCRDWHP(MNUMOR,MNUMYR)	$87/bbl	Expected domestic crude wellhead price
XRFQDCRD(MNUMOR,MNUMYR)	MMbbl/yr	Expected domestic crude production
ADVETHCD(MNUMCR,MNUMYR)	Mbbl/cd	Advanced ethanol
BIMQTYCD(4,MNUMCR,MNUMYR)	MMbbl/cd	Quantity Biodiesel Produced by Type
BIODIMP(MNUMCR,MNUMYR)	MMbbl/cd	Biodiesel Imports
BIODPRICE(MNUMCR,MNUMYR)	$87/bbl	Biodiesel Price
BLDIMP(MNUMPR, MNUMYR)	MMbbl/cd	Blending Component Imports
CLLETHCD(MNUMCR, MNUMYR)	Mbbl/cd	Ethanol Produced from Cellulose
CORNACRE(MNUMCR,MNUMYR)	Million Acres	Total Acreage Devoted to Growing Corn
CORNCROP(MNUMCR,MNUMYR)	MMbushels	Total Corn Crop
CORNEXP(MNUMCR,MNUMYR)	MMbushels	Net Corn Exports
CRNCD(MNUMCR,MNUMYR)	MM bushels/yr	Corn consumption by CD
CRNETHCD(MNUMCR, MNUMYR)	Mbbl/cd	Ethanol produced from corn
DSSTTX(MNUMCR)	$87/bbl	Diesel State Tax
ETHEXP(MNUMCR,MNUMYR)	Mbbl/cd	Ethanol Exports
ETHE85CD(MNUMCR, MNUMYR)	Mbbl/cd	Total ethanol used for E85 production
ETHGASCD(MNUMCR,MNUMYR)	Mbbl/cd	Ethanol blended into motor gasoline (not used)
ETHIMP(MNUMCR,MNUMYR)	Mbbl/cd	Ethanol Imports
ETHTOTCD(MNUMCR, MNUMYR)	Mbbl/cd	Total ethanol used
GRNETHCD(MNUMCR,MNUMYR)	Mbbl/cd	Non-corn, non-advanced, ethanol produced from grain
GRSMRGN(MNUMPR, MNUMYR)	$87/yr	Gross margin
JFSTTX(MNUMCR)	$87/bbl	Jet Fuel State Tax
MGSTTX(MNUMCR)	$87/bbl	Gasoline State Tax
MUFTAX(MNUMYR,15)	$87/MMBtu	Federal motor gasoline tax
OTHETHCD(MNUMCR,MNUMYR)	Mbbl/cd	Ethanol produced from other feedstock
PETHANOL(MNUMCR,MNUMYR)	$87/bbl	Price of corn ethanol in CD
PETHM(MNUMCR,MNUMYR)	$87/bbl	Marginal price for ethanol
QPRDRF(MNUMPR, MNUMYR,30)	Mbbl/cd	Refinery production volumes
QPRDEX(MNUMCR,30, MNUMYR)	Mbbl/cd	Refinery production exported
RFBDSTCAP(MNUMPR, MNUMYR)	MMbbl/cd	Refinery base distillation capacity
RFCRDOTH(MNUMPR, MNUMYR)	MMbbl/cd	Other crude imports by PAD District
RFDPRDAST(MNUMPR, MNUMYR)	Mbbl/cd	Refinery production; asphalt & road oil
RFDPRDCOK(MNUMPR, MNUMYR)	Mbbl/cd	Refinery production; petroleum coke

Other LFMM Output Arrays		
NAME	**UNITS**	**DEFINITION**
RFDPRDDSL(MNUMPR, MNUMYR)	Mbbl/cd	Refinery production; low sulfur diesel
RFDPRDDSU(MNUMPR, MNUMYR)	Mbbl/cd	Refinery production; ultra low sulfur diesel
RFDPRDJTA(MNUMPR, MNUMYR)	Mbbl/cd	Refinery production; jet fuel
RFDPRDKER(MNUMPR, MNUMYR)	Mbbl/cd	Refinery production; kerosene
RFDPRDLPG(MNUMPR, MNUMYR)	Mbbl/cd	Refinery production; LPG
RFDPRDN2H(MNUMPR,MNUMYR)	Mbbl/cd	Refinery production; no. 2 distillate
RFDPRDN6B(MNUMPR,MNUMYR)	Mbbl/cd	Refinery production; high sulfur oil
RFDPRDN6I(MNUMPR,MNUMYR)	Mbbl/cd	Refinery production; low sulfur residual oil
RFDPRDOTH(MNUMPR,MNUMYR)	Mbbl/cd	Refinery production; other petroleum
RFDPRDPCF(MNUMPR,MNUMYR)	Mbbl/cd	Refinery production; petrochemical feeds
RFDPRDRFG(MNUMPR,MNUMYR)	Mbbl/cd	Refinery production; reformulated motor gasoline
RFDPRDRFH(MNUMPR,MNUMYR)	Mbbl/cd	Refinery prd; reform. hi oxygen motor gasoline
RFDPRDSTG(MNUMPR,MNUMYR)	Mbbl/cd	Refinery production; still gas
RFDPRDTRG(MNUMPR,MNUMYR)	Mbbl/cd	Refinery production; motor gasoline
RFDPRDTRH(MNUMPR,MNUMYR)	Mbbl/cd	Refinery prd; high oxygenated motor gasoline
RFDPRDTRL(MNUMPR,MNUMYR)	Mbbl/cd	Domestic production of low sulfur gasoline
RFDSCUM(MNUMPR,MNUMYR)	MMbbl/cd	Processing unit cumulative cap. Expansion
RFDSTCAP(MNUMPR,MNUMYR)	Mbbl/cd	Refinery distillation capacity
RFDSTUTL(MNUMPR,MNUMYR)	Percent	Capacity utilization rate
RFETHD(MNUMYR)	MMbbl/cd	Domestic ethanol
RFETHE85(MNUMPR,MNUMYR)	MMbbl/cd	Ethanol for E85 production
RFIMCR(MNUMPR,MNUMYR)	MMbbl/YR	Crude net imports
RFIMTP(MNUMPR,MNUMYR)	MMbbl/YR	Total prod net imports
RFIPQCBOB(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Imports CBOB (P,Q)
RFIPQCHH(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Import crude-high sulfur heavy
RFIPQCHL(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Import crude high sulfur light
RFIPQCHV(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Import crude high sulfur very heavy
RFIPQCLL(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Import crude low sulfur light (P,Q)
RFIPQCMH(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Import crude medium sulfur heavy
RFIPQDL(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Imported low sulfur distillate (P,Q)
RFIPQDS(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Imports distillate (P,Q)
RFIPQDU(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Imports ultra low sulfur distillate (P,Q)
RFIPQJF(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Imports jet fuel (P,Q)
RFIPQLFC(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Imports liquids from coal (P,Q)
RFIPQLFG(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Imports liquids from natural gas (P,Q)
RFIPQLG(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Imports lpg (P,Q)
RFIPQME(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Imports methanol (P,Q)
RFIPQMG(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Imports motor gasoline (P,Q)
RFIPQMT(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Imports mtbe (P,Q)
RFIPQOT(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Imported other (P,Q)
RFIPQPF(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Imported petrochemical feeds (P,Q)
RFIPQRBOB(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Imports reformulated gasoline before oxygenate blending (P,Q)
RFIPQRG(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Imported reformulated motor gasoline (P,Q)
RFIPQRH(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Imports high sulfur resid (P,Q)

Other LFMM Output Arrays		
NAME	**UNITS**	**DEFINITION**
RFIPQRL(MNUMPR,MNUMYR,2)	$87/bbl,Mbbl/cd	Imports low sulfur resid (P,Q)
RFMETCHM(MNUMPR,MNUMYR)	MMbbl/cd	Chemical methanol demand
RFMETD(MNUMYR)	MMbbl/cd	Domestic methanol
RFMETI(MNUMPR,MNUMYR)	MMbbl/cd	Imported methanol
RFMETM85(MNUMPR,MNUMYR)	MMbbl/cd	Methanol for M85 production
RFMTBD(MNUMPR,MNUMYR)	MMbbl/cd	Domestic MTBE production.
RFMTBI(MNUMPR,MNUMYR)	MMbbl/cd	Imported MTBE
RFPQIPRDT(MNUMPR,MNUMYR,2)	$87/bbl,MMbbl/cd	Total imported product
RFPQUFARB(MNUMPR,MNUMYR,2)	MMbbl/cd	Imports unfinished oils – residuum
RFPQUFC(MNUMPR,MNUMYR,2)	MMbbl/cd	Total imports of unfinished crude
RFPQUFHGM(MNUMPR,MNUMYR,2)	MMbbl/cd	Imports unfinished oils – heavy gas oils
RFPQUFNPP(MNUMPR,MNUMYR,2)	MMbbl/cd	Imports unfinished oils – naphtha and lighter
RFQARO(MNUMCR,MNUMYR)	MMbbl/cd	Quantity of asphalt and road oil
RFQDS(MNUMCR,MNUMYR)	MMbbl/cd	Quantity of distillate fuel oil
RFQEXCRD(MNUMPR,MNUMYR)	MMbbl/cd	Crude exported
RFQEXPRDT(MNUMPR,MNUMYR)	MMbbl/cd	Total product exported
RFQICRD(MNUMPR,MNUMYR)	MMbbl/cd	Imported total crude
RFQJF(MNUMCR,MNUMYR)	MMbbl/cd	Quantity of jet fuel
RFQKS(MNUMCR,MNUMYR)	MMbbl/cd	Quantity of kerosene
FQLG(MNUMCR,MNUMYR)	MMbbl/cd	Quantity of lpg
RFQMG(MNUMCR,MNUMYR)	MMbbl/cd	Quantity of motor gasoline
RFQOTH(MNUMCR,MNUMYR)	MMbbl/cd	Quantity of other
RFQPCK(MNUMCR,MNUMYR)	MMbbl/cd	Quantity of petroleum coke
RFQPF(MNUMCR,MNUMYR)	MMbbl/cd	Quantity of petrochemical feedstocks
RFQRH(MNUMCR,MNUMYR)	MMbbl/cd	Quantity of resid high sulfur
RFQRL(MNUMCR,MNUMYR)	MMbbl/cd	Quantity of resid low sulfur
RFQSTG(MNUMCR,MNUMYR)	MMbbl/cd	Quantity of still gas
SBOQGDCD(MNUMCR,MNUMYR)	Mbbl/cd	Quantity of green naphtha/diesel from SBO
TDIESEL(MNUMCR,MNUMYR)	Mbbl/cd	Total diesel in all sectors
TOTPRD(MNUMPR,MNUMYR)	MMbbl/cd	Total refinery product sold
WGRQGDCD(MNUMCR,MNUMYR)	Mbbl/cc	Quantity of green naphtha/diesel from WGR
YGRQGDCD(MNUMCR,MNUMYR)	Mbbl/cd	Quantity of green naphtha/diesel from YGR
CGRECAP(MNUMCR,MJUMPYR,5,2,2)	MW	Refinery CHP Capacity
CGREQ(MNUMCR,MJUMPYR,5,2)	TrillBtu	Refinery Fuel Consumption
ORCLPMM	None	DB transfer variable
PCHCOLVALS(PMAXCOLS,PMAXRECS)	None	DB transfer variable
PCHCOLV(PMAXTABS,PMAXCOLS,PMAXRECS)	None	DB transfer variable
PCOLVALS(PMAXCOLS,PMAXRECS)	None	DB transfer variable
PCOLV(PMAXTABS,PMAXCOLS,PMAXRECS)	None	DB transfer variable
PDYNSTM(PMAXTABS)	None	DB transfer variable
PFNRUN	None	DB transfer variable
PLOOPING(PMAXTABS)	None	DB transfer variable
PMAXRECS=100	None	DB transfer variable
PNUMCOLS(PMAXTABS)	None	DB transfer variable

Other LFMM Output Arrays		
NAME	**UNITS**	**DEFINITION**
PTNUM	None	DB transfer variable

Refinery Aggregation Study

Pending.