# Co-Product Function Expansion

***A Methodology for Incrementally Considering the Effects of Co-Products in Multi-Product Systems***

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# Overview

- Co-production Function Expansion Motivation
- CFE Methodology
- Case Study
- Conclusions

# Motivation

- Develop methodology for multi-product systems
- Evaluating effects of alternative methodologies
  - Allocation
  - System Boundary Expansion
- Allow individual co-products to be assessed within the full product system
- SBE may require considerable data and resources
- Methodology developed as part of the ConocoPhillips Ultra Clean Fuels LCA, supported by the Ultra Clean Fuels Initiative of the Department of Energy
  - UCF LCA report soon to be published
  - Study and CFE methodology received ISO 14040 endorsement from independent peer review panel

# *Co-Product Function Expansion*

- **CFE is an incremental approach**
- **CFE is particularly relevant for co-products that have potentially significant impacts**
- **Definitions:**
  - **Primary products are defined as those outputs of a production system that are the primary economic drivers of the system or industry.**
  - **Co-products are outputs that may have economic value, but would not be produced if not for the production of the primary products.**

# *CFE (Continued)*

- **CFE scope is defined with respect to market information and to a specific set of co-product functions**

- **An example of the CFE methodology is presented through an application to petroleum refining**
  - **In petroleum refining the primary economic drivers of the system are transportation fuels for motor vehicles**
  - **Petroleum coke and heavy residual oil evaluated**

# Methodology

- **Define CFE Scope**
  - Specify the co-products, co-product functions, and product alternatives that are considered.
  - Only co-product functions for which there are reasonable economic and technical product alternatives are considered.
  - Otherwise, allocation is used and the remaining portions of the co-products are placed outside the system boundary.
  - A reference product slate is selected, chosen on the basis of national or regional average, or for a representative production facility.

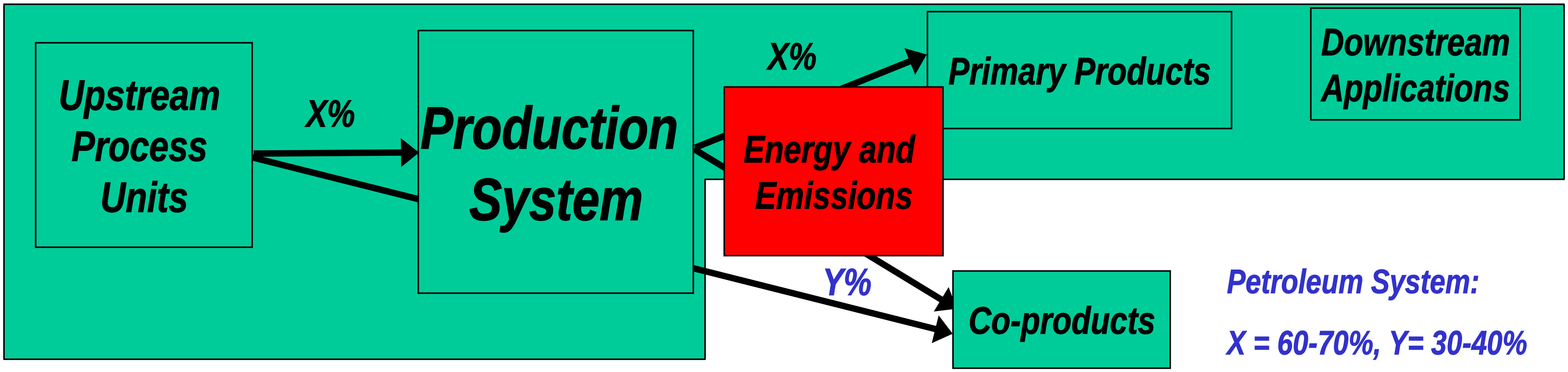
- **The energy and emissions due to the portion of the co-products (for upstream and production stages) considered in the CFE are assigned to the primary products based on the mass or energy content of the product slate**

# *Methodology (Continued)*

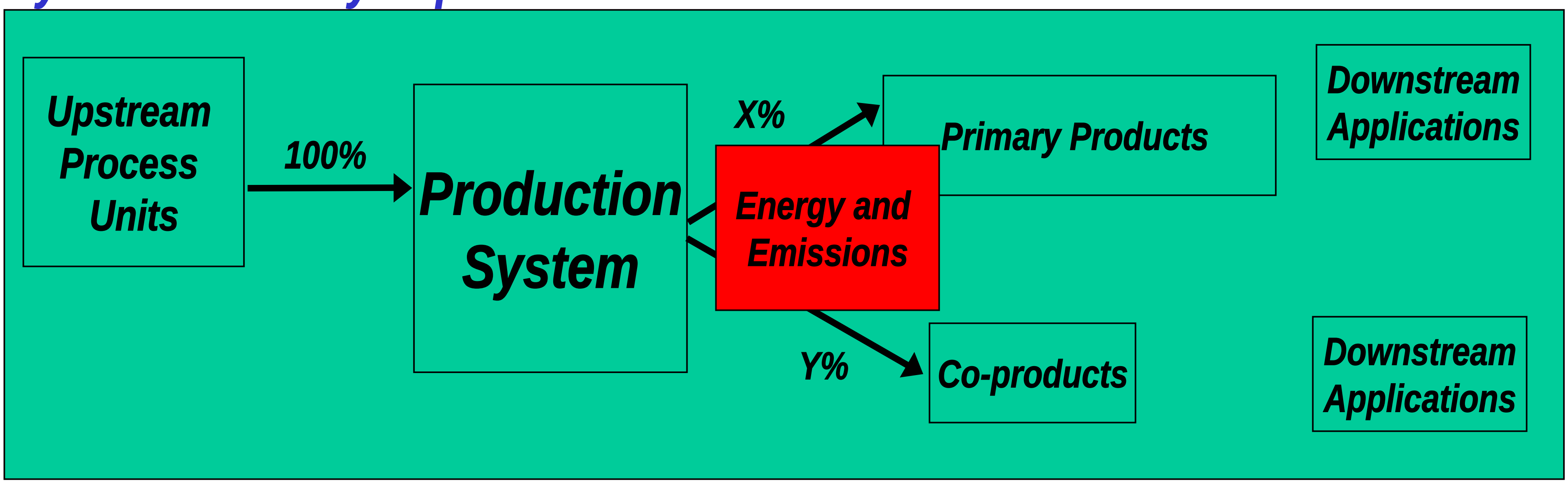
- **The co-products are compared with alternative products in downstream applications**
- **The net energy and emissions inventories are assigned as either credits or debits to the primary products.**
- **The energy and emissions for alternative products must include the full life cycle inventories**
- **The overall functional unit for the CFE is the same functional unit as for the primary system product or products.**

# System Boundaries: Allocation and System Boundary Expansion

## Allocation

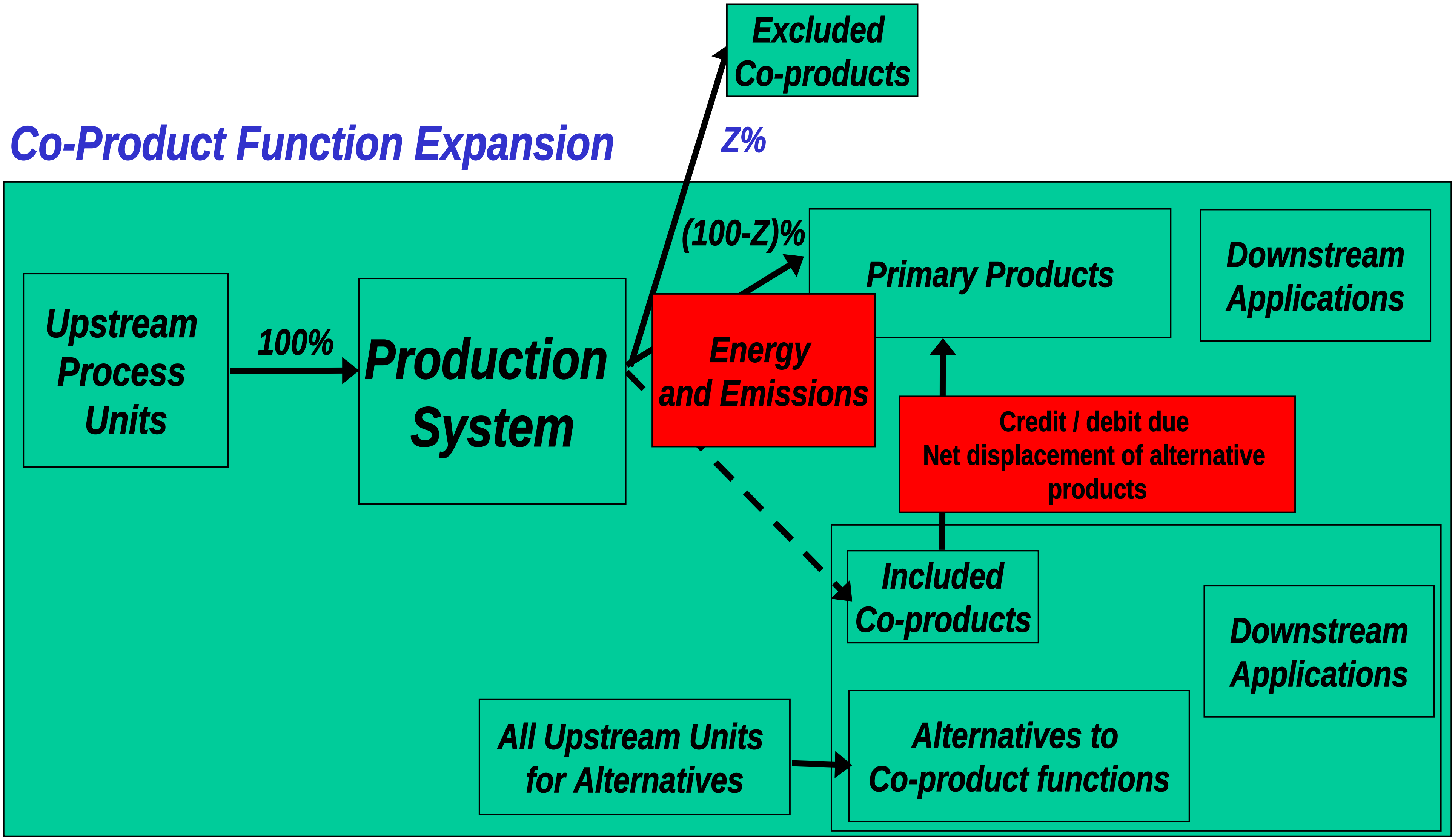



## System Boundary Expansion



# System Boundary: Co-Product Function Expansion

## Co-Product Function Expansion

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# *Application of CFE*

- **Application to Petroleum Refining**
  - **Petroleum coke and heavy residual oil, two "less desirable" co-products, are considered.**
  - **Petroleum coke and heavy residual oil potentially have considerable potential environmental impact in downstream applications.**
  - **Petroleum product slate is based on PADD III for 2006 and 2015. Crude slate becomes heavier over that period.**
  - **LCA modeling carried out with GREET, PIMS, and AspenPlus**
- **Gasoline and diesel motor fuels are primary products of petroleum refining.**
- **Co-products asphalt, fuel oil, naphtha, kerosene/jet fuel, and liquefied petroleum gas (LPG) are placed outside the system boundary.**

| Co-Product | Application | Alternative Products | |
|---|---|---|---|
| | | 2006 | 2015 |
| Petroleum coke | Power | Coal | Natural gas |
| | Cement | Coal | Coal |
| Heavy residual oil | Power | Natural gas | Natural gas |
| | Heat/steam | Natural gas | Natural gas |

# Petroleum Coke

- Petroleum coke is used in downstream applications such as power generation, cement production, metallurgy, and the production of high-grade carbon fiber products.
- In 1999, a total of 48 millions tonnes of petroleum coke was produced globally (Energy Information Agency, 2001)
  - 14% of which was used for power generation
  - 40% for cement production
  - 22% for anodes and other high-grade carbon fiber products
  - 24% for metallurgy
- The U.S. produces 75% of fuel grade coke used globally, and exports 55% of its domestic production.
- Most power generation and cement production occurs overseas, in Asia and Europe
- The CFE considers only power and cement applications, which account for 54% of global coke use. Carbon fiber and metallurgy applications are not considered in the CFE.

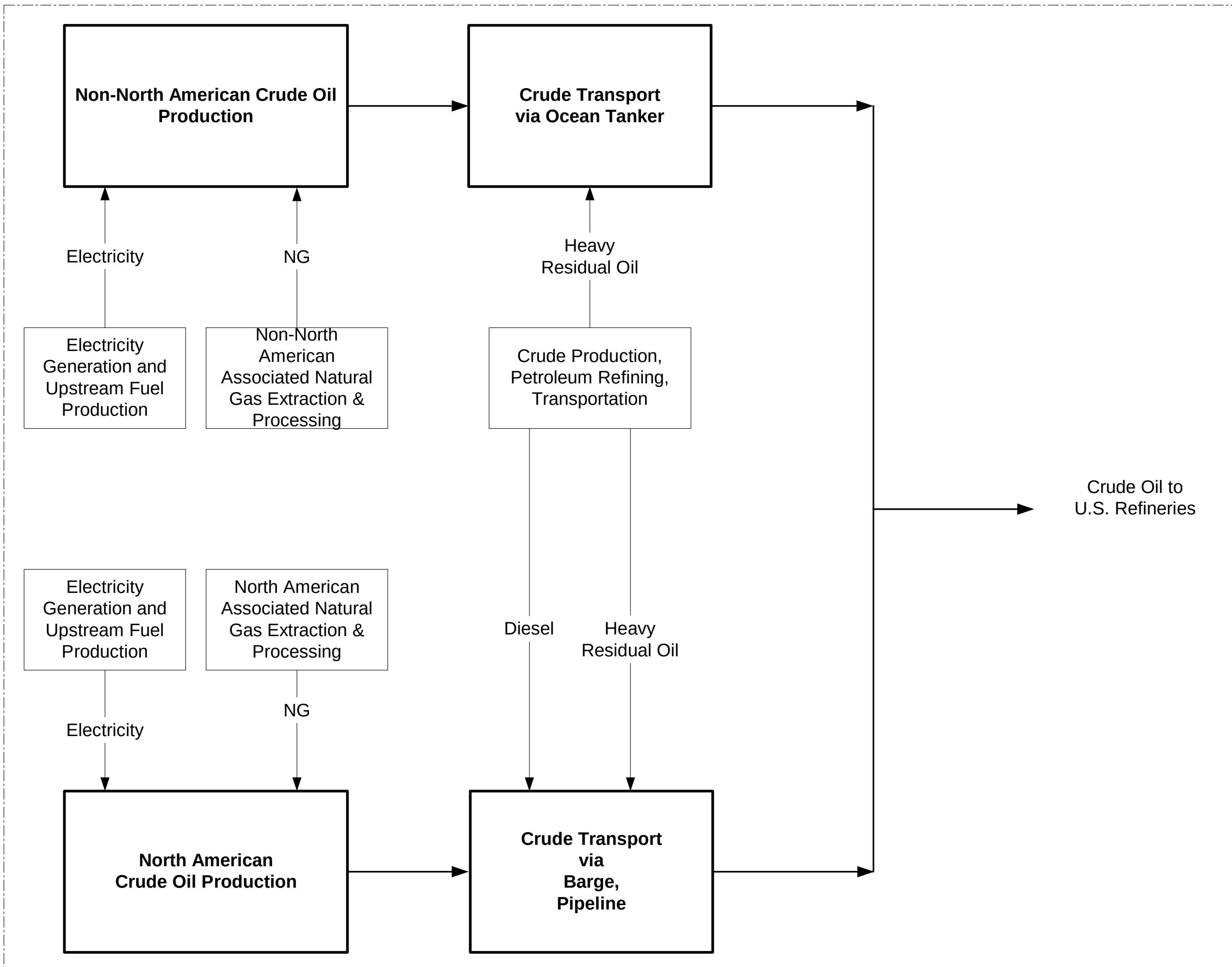
# *Heavy Residual Oil*

- **33% of heavy residual fuel oil produced in the U.S. is used in electricity generation**
- **17% is used in industrial applications for process heat and steam generation.**
- **49% is used in marine transportation.**
- **Heavy residual oil is used to generate about 1.5% of the power produced in the U.S.   HRO is often co-fired with natural gas when gas inventory or price necessitates an alternative (EIA, 2001).**
- **Marine transportation is not considered in the CFE.**

# *Pet Coke and Heavy Residual Oil as Waste Products*

- **Sulfur and metals concentrations in coke and residual oil are increasing**
- **In the future, high sulfur, high-metals residual fuels and coke may even become wastes**
- **Under the allocation methodology:**
  - **The associated energy, emissions and toxic impacts for coke and heavy residual oil should be allocated to primary products**
- **Under the system boundary expansion methodology:**
  - **Impacts from coke and heavy residual oil, if co-products or waste, must be accounted for within the system boundary**

# System Boundary: Crude Production

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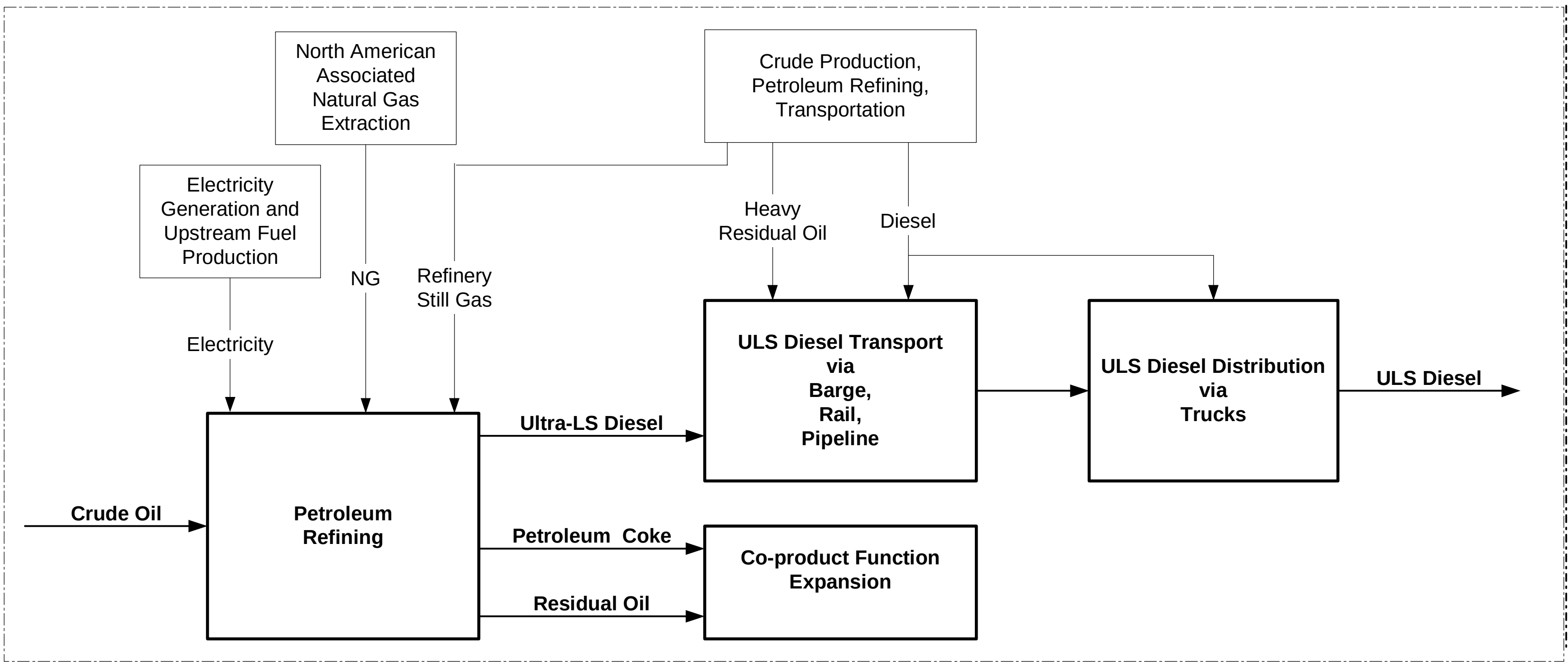
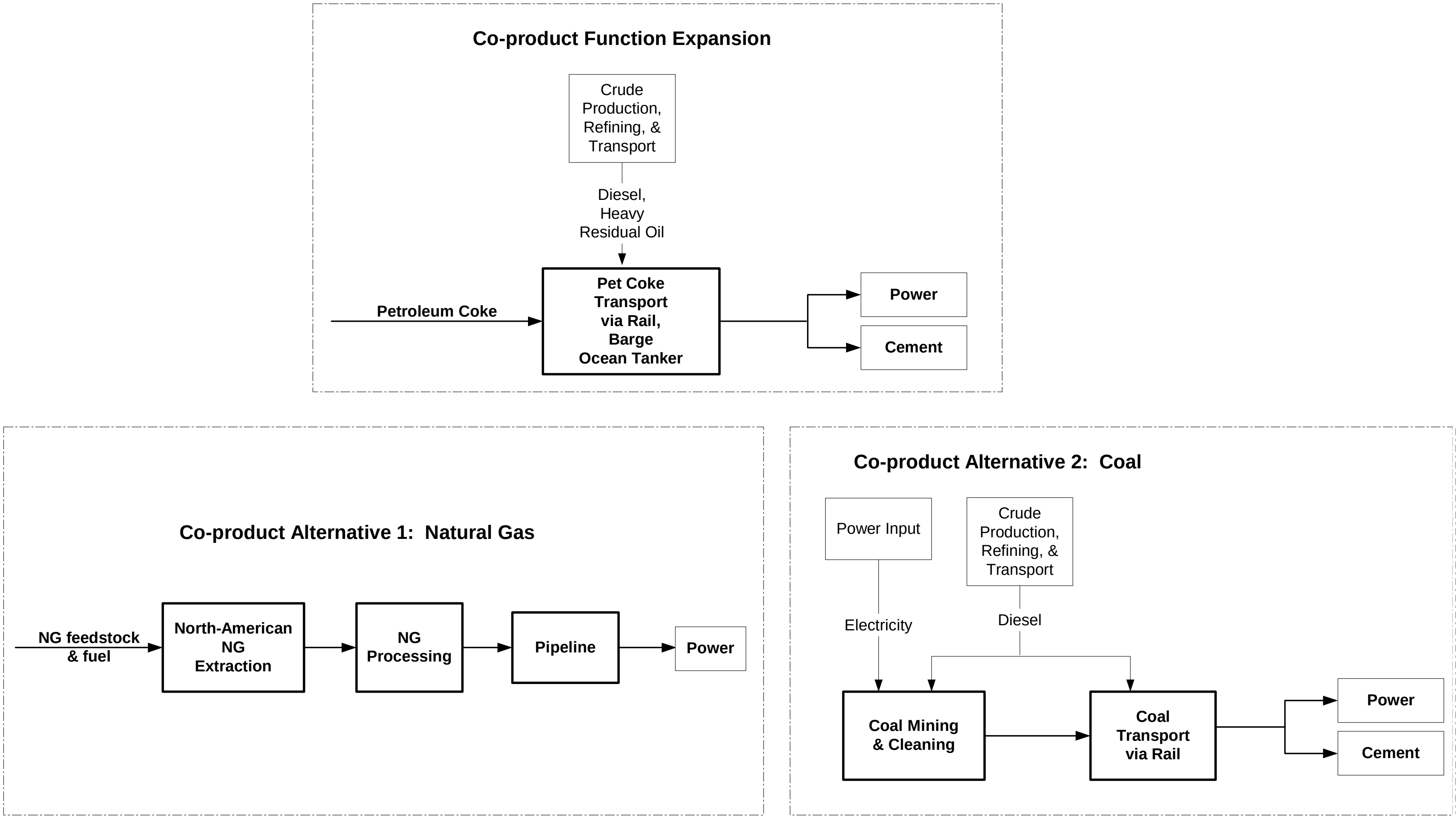
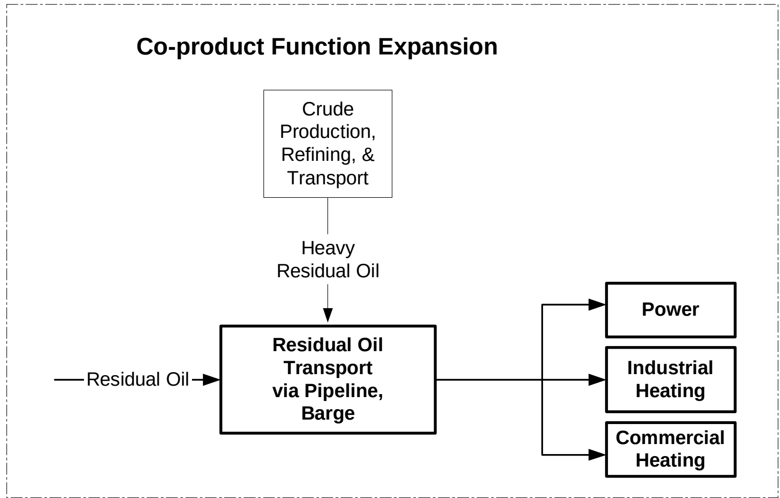
# System Boundary: Petroleum Refining and Transport

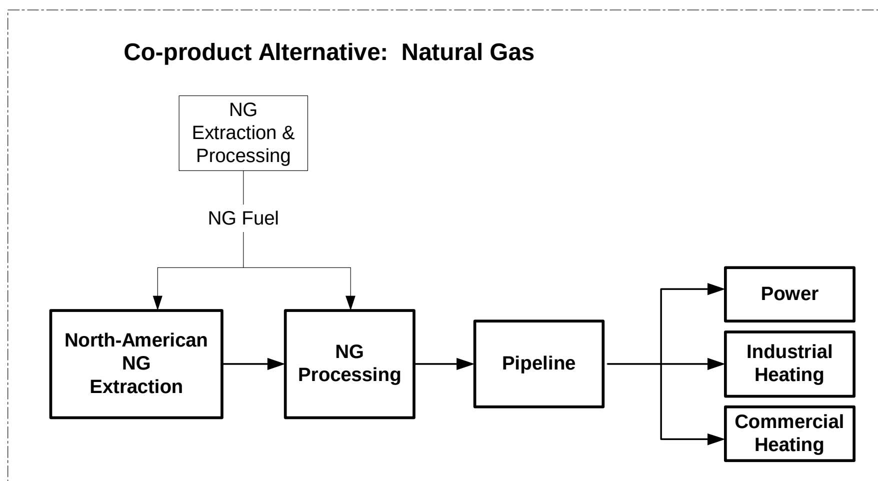


# System Boundary: CFE for Coke

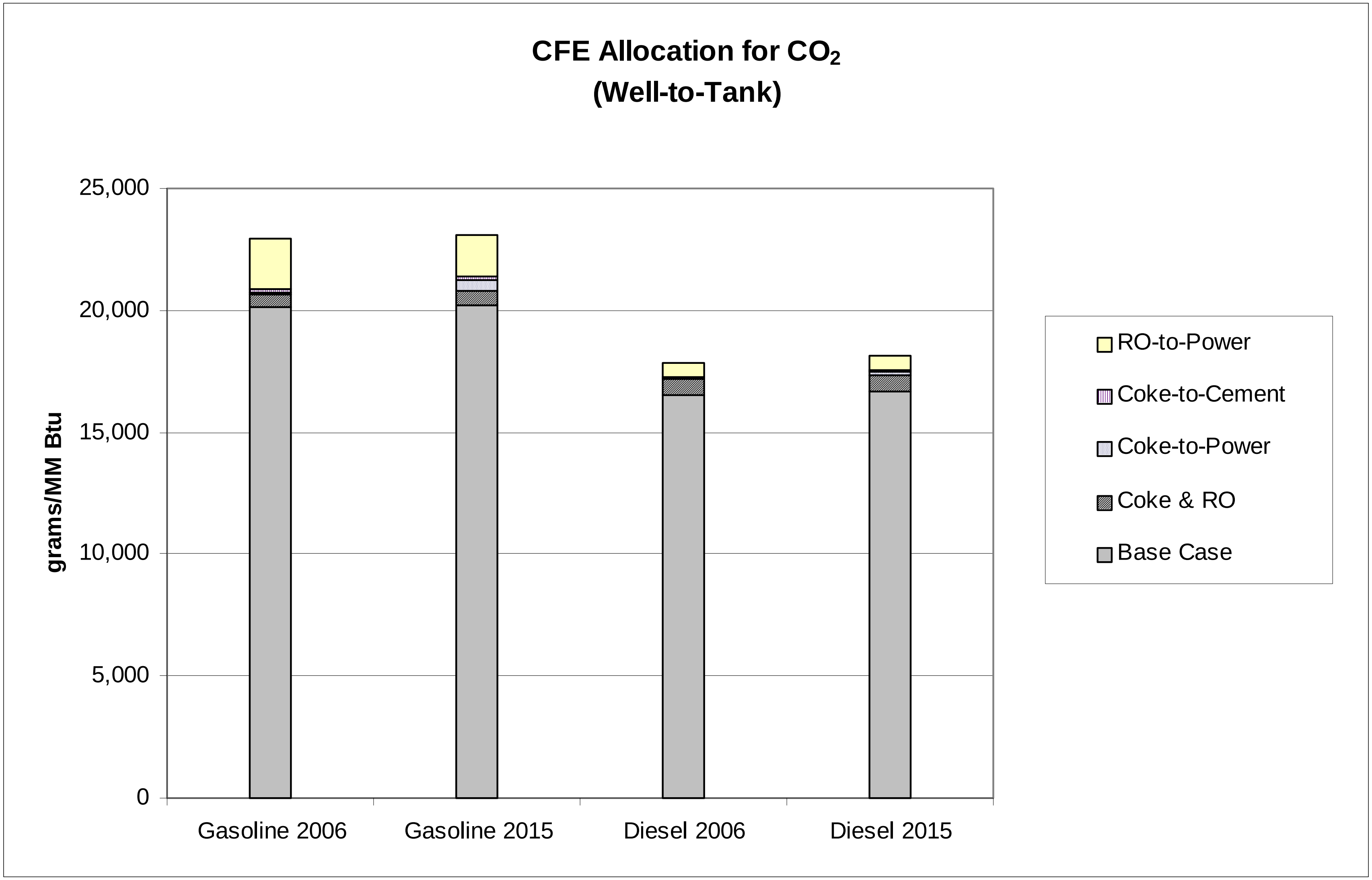


# System Boundary: CFE for Residual Oil

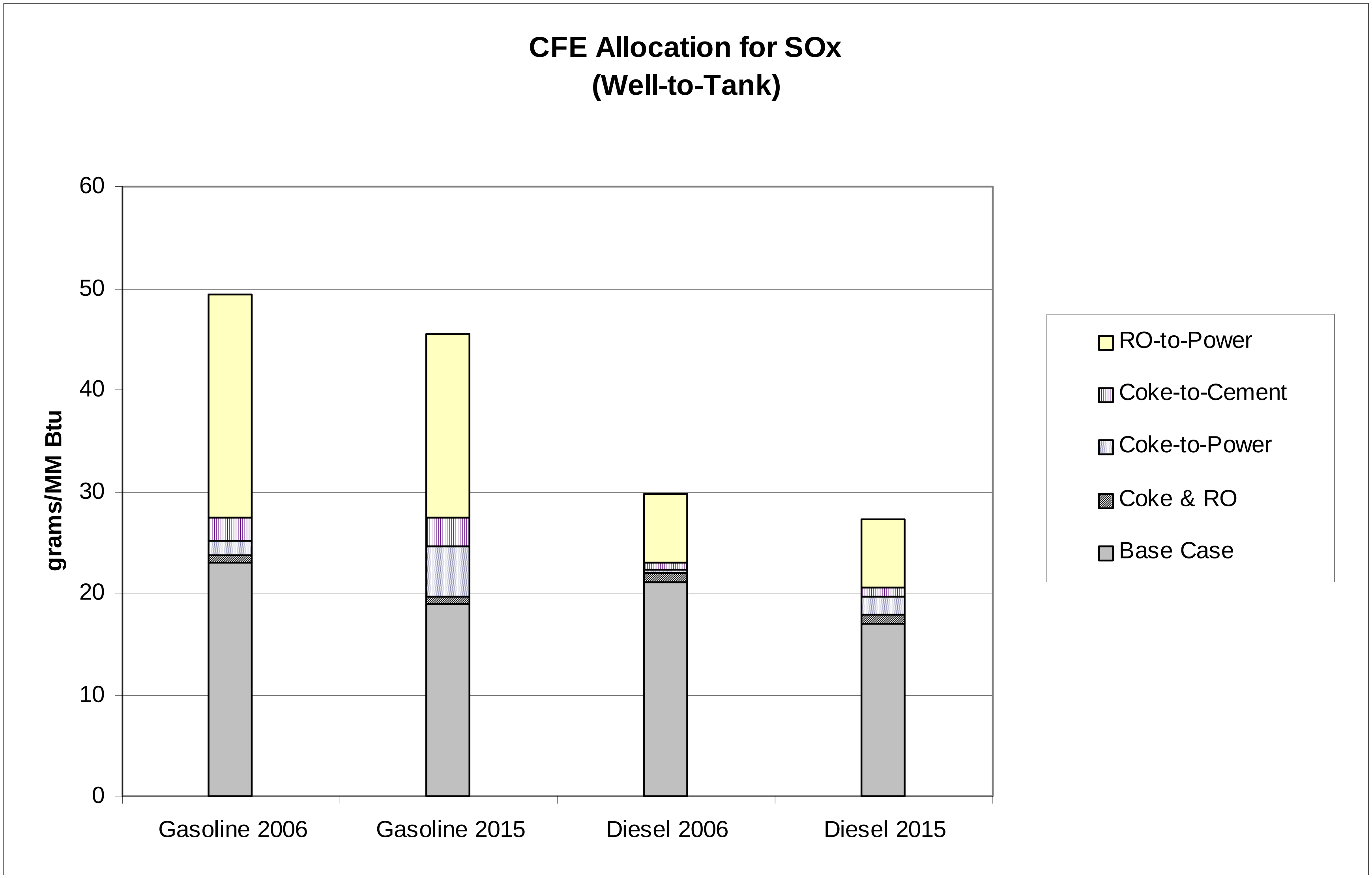


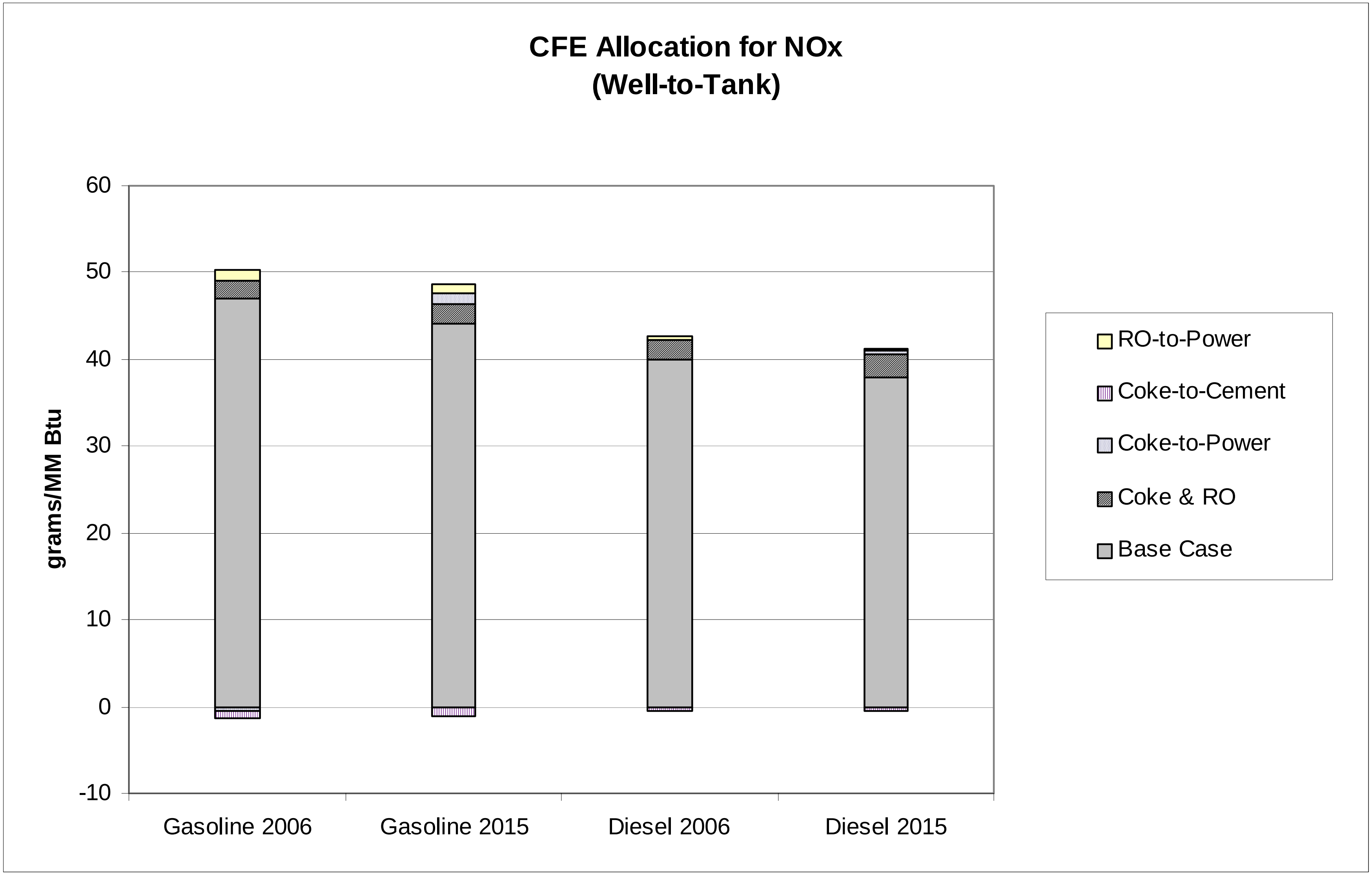
# CFE Results: $CO_2$



# CFE Results: $SO_X$



# CFE Results: $NO_X$



# CFE Results

| | $CO_2$ | $SO_x$ | $NO_x$ |
|---|---|---|---|
| No co-products case | 20,111 | 23 | 47 |
| Coke and RO production | 566 | 0.8 | 2.1 |
| Coke-to-power (vs. coal) | 43 | 1.4 | -0.4 |
| Coke-to-cement (vs. coal) | 126 | 2.2 | -0.9 |
| RO-to-power (vs. NG) | 2097 | 22 | 1.1 |
| Total CFE | 22,943 | 49 | 49 |
| Increase over no co-products case, % | 14.0% | 118.6% | 4.0% |

CFE for Gasoline, Increases over 2006 Base Case (g/MMBtu of Gasoline)

| | $CO_2$ | $SO_x$ | $NO_x$ |
|---|---|---|---|
| No co-products case | 16,544 | 21 | 40 |
| Coke and RO production | 627 | 0.9 | 2.3 |
| Coke-to-power (vs. coal) | 13 | 0.4 | -0.1 |
| Coke-to-cement (vs. coal) | 38 | 0.7 | -0.3 |
| RO-to-power (vs. NG) | 642 | 6.8 | 0.3 |
| Total CFE | 17,865 | 29 | 42 |
| Increase over no co-products case, % | 8.0% | 42.6% | 5.7% |

CFE for Ultra-Low-Sulfur Diesel, Increases over 2006 Base Case (g/MMBtu)

| | $CO_2$ | $SO_x$ | $NO_x$ |
|---|---|---|---|
| No co-products case | 20,206 | 19 | 44 |
| Coke and RO production | 602 | 0.7 | 2.3 |
| Coke-to-power (vs. NG) | 424 | 4.9 | 1.4 |
| Coke-to-cement (vs. coal) | 155 | 2.8 | -1.1 |
| RO-to-power (vs. NG) | 1,729 | 18 | 0.9 |
| Total CFE | 23,116 | 45 | 48 |
| Increase over no co-products case, % | 14.4% | 139% | 8.0% |

CFE for Gasoline, Increases over 2015 Base Case (g/MMBtu)

| | $CO_2$ | $SO_x$ | $NO_x$ |
|---|---|---|---|
| No co-products case | 16,667 | 17 | 38 |
| Coke and RO production | 668 | 0.8 | 2.5 |
| Coke-to-power (vs. NG) | 153 | 1.8 | 0.5 |
| Coke-to-cement (vs. coal) | 56 | 1.0 | -0.4 |
| RO-to-power (vs. NG) | 626 | 6.6 | 0.3 |
| Total CFE | 18,170 | 27.4 | 40.4 |
| Increase over no co-products case, % | 9.0% | 59.3% | 7.7% |

CFE for Ultra-Low-Sulfur Diesel, Increases over 2015 Base Case (g/MMBtu)

# Conclusions

- The CFE methodology provides an efficient means of considering selected co-products in multi-product systems
- CFE provides a means of assessing the sensitivity of multi-product systems to co-products
- The CFE as applied to petroleum refining:
  - Indicates that there is a quantifiable increase in emissions inventory
  - The magnitude of the differences depends upon the market assumption for the CFE for and assumptions about the alternatives for the co-products in downstream applications.
  - Only a portion of total refinery production of petroleum coke and heavy residual oil was included in the analysis.

# CFE Background Data: Coke, Natural Gas and Coal to Power

**Table 3 Petroleum Coke-to-Power Parameters**

| Parameter | U.S. | Japan, Europe, Canada | Asia and Latin America |
|---|---|---|---|
| Sulfur content, % | 6 | 6 | 6 |
| Desulfurization efficiency, % | 90.0% | 90.0% | 10.0% |
| Power generation efficiency, % | 35.0% | 35.0% | 30.0% |
| Fuel heating value, Btu/lb | 13,337 | 13,337 | 13,337 |
| $SO_x$ emission factor constant, lb/tonne (uncontrolled) | 234 | 234 | 234 |
| $NO_x$ emission factor, lb/tonne | 21 | 21 | 21 |
| $NO_x$ reduction factor, % | 30% | 30% | 0% |
| $CO_2$ emission factor, lb/MMBtu | 225 | 225 | 225 |

Source: EIA, US EPA AP-42 Emissions Factors

**Table 4 Coal-to-Power Parameters**

| Parameter | U.S. | Japan, Europe, Canada | Asia and Latin America |
|---|---|---|---|
| Sulfur content, % | 3 | 3 | 3 |
| Desulfurization efficiency, % | 90.0% | 90.0% | 10.0% |
| Power generation efficiency, % | 35.0% | 35.0% | 30.0% |
| Fuel heating value, Btu/lb | 10,825 | 10,825 | 10,825 |
| $SO_X$ emission factor constant, lb/tonne | 114 | 114 | 114 |
| $NO_X$ emission factor, lb/tonne | 63 | 63 | 63 |
| $NO_X$ reduction factor, % | 30% | 30% | 0% |
| $CO_2$ emission factor, lb/MMBtu | 205 | 205 | 205 |

Source: EIA, US EPA AP-42 Emissions Factors

**Table 5 Natural Gas-to-Power Parameters**

| Parameter | U.S. | Japan, Europe, Canada | Asia and Latin America |
|---|---|---|---|
| Sulfur content, % | 0.05 | 0.05 | 0.05 |
| Power generation efficiency, % | 50.0% | 50.0% | 45.0% |
| Fuel heating value, Btu/cu ft | 1,031 | 1,031 | 1,031 |
| $SO_X$ emission factor constant, lb/$10^6$ cu ft | 0.6 | 0.6 | 0.6 |
| $NO_X$ emission factor, lb/$10^6$ cu ft | 170 | 170 | 170 |
| $NO_X$ reduction factor, % | 30% | 30% | 0% |
| $CO_2$ emission factor, lb/MMBtu | 116 | 116 | 116 |

Source: EIA, US EPA AP-42 Emissions Factors

# CFE Background Data: Coke to Cement

**Table 6 Petroleum Coke-to-Cement Parameters**

| Parameter | Petroleum Coke | | | Coal |
|---|---|---|---|---|
| | Asia | Europe | Latin America | Average |
| Sulfur content, % | 6 | 6 | 6 | 6 |
| Desulfurization efficiency, % | 90.0% | 90.0% | 90.0% | 90.0% |
| Fuel heating value, Btu/lb (HHV) | 13,337 | 13,337 | 13,337 | 12,000 |
| $SO_X$ emission factor, kg/tonne of cement | 4.9 | 4.9 | 4.9 | 4.8 |
| $NO_X$ emission factor, kg/tonne of cement | 3 | 3 | 3 | 3 |
| Total $CO_2$ emission factor, kg/tonne of cement | 900 | 900 | 900 | 820 |
| Energy requirement, MMBtu/tonne of cement | 4.336 | 4.336 | 4.336 | 4.336 |

Source: EIA, US EPA AP-42 Emissions Factors

# CFE Background Data: Resid and Natural Gas to Power, Heat/Steam

**Table 7 Heavy Residual Oil-to-Power and to-Heat/Steam Parameters, U.S.**

| Parameter | Electric Utilities | Industrial Heat/Steam | Commercial Heat/Steam |
|---|---|---|---|
| Sulfur content, % | 3 | 3 | 3 |
| Desulfurization efficiency, % | 90.0% | 0.0% | 0.0% |
| Power or steam generation efficiency, % | 38.0% | 80.0% | 85.0% |
| Fuel heating value, Btu/gal | 151,470 | 151,470 | 151,470 |
| $SO_X$ emission factor constant, lb/$10^3$ gal | 157 | 157 | 157 |
| $NO_X$ emission factor, lb/$10^3$ gal | 32 | 32 | 32 |
| $NO_X$ reduction factor, % | 30% | 30% | 0% |
| $CO_2$ emission factor, lb/MMBtu | 174 | 174 | 174 |

*Source: EIA, US EPA AP-42 Emissions Factors*

**Table 8 Natural Gas-to-Power and to-Heat/Steam Parameters, U.S.**

| Parameter | Electric Utilities | Industrial Heat/Steam | Commercial Heat/Steam |
|---|---|---|---|
| Sulfur content, % | .05 | .05 | .05 |
| Desulfurization efficiency, % | 0.0% | 0.0% | 0.0% |
| Power generation efficiency, % | 50.0% | 85.0% | 90.0% |
| Fuel heating value, Btu/cu ft | 928 | 928 | 928 |
| $SO_X$ emission factor constant, lb/$10^6$ cu ft | 0.6 | 0.6 | 0.6 |
| $NO_X$ emission factor, lb/$10^6$ cu ft | 170 | 170 | 170 |
| $NO_X$ reduction factor, % | 30% | 30% | 0% |
| $CO_2$ emission factor, lb/MMBtu | 116 | 116 | 116 |

*Source: EIA, US EPA AP-42 Emissions Factors*

# CFE Background Data: CFE Allocations to Gasoline and Diesel

**Table 9 PADD III 2006—Co-Product Energy and Emissions Allocations to Gasoline (Btu/MMBtu or gm/MMBtu)**

| | Allocation Approach, No Co-products | Coke and RO |
|---|---|---|
| Total energy | 266,490 | 7,635 |
| $CO_2$ | 20,111 | 566 |
| $NO_X$ | 46.76 | 2.08 |
| $SO_X$ | 22.60 | 0.81 |

**Table 10 PADD III 2006—Co-Product Energy and Emissions Allocations to Diesel (Btu/MMBtu or gm/MMBtu)**

| | Allocation Approach, No Co-products | Coke and RO |
|---|---|---|
| Total energy | 214,562 | 8,499 |
| $CO_2$ | 16,544 | 626 |
| $NO_X$ | 39.83 | 2.32 |
| $SO_X$ | 20.68 | 0.90 |

**Table 11 PADD III 2015—Co-product Energy and Emissions Allocations to Gasoline (Btu/MMBtu or gm/MMBtu)**

| | Allocation Approach, No Co-products | Coke and RO |
|---|---|---|
| Total energy | 268,328 | 8,128 |
| $CO_2$ | 20,206 | 603 |
| $NO_X$ | 43.92 | 2.23 |
| $SO_X$ | 18.76 | 0.74 |

**Table 12 PADD III 2015—Co-product Energy and Emissions Allocations to Diesel (Btu/MMBtu or gm/MMBtu)**

| | Allocation Approach, No Co-products | Coke and RO: |
|---|---|---|
| Total energy | 216,692 | 9,048 |
| $CO_2$ | 16,667 | 669 |
| $NO_X$ | 37.51 | 2.48 |
| $SO_X$ | 17.20 | 0.82 |

# *CFE Background Data: Coke 2006 and 2015 net changes*

**Table 13 Coke-to-Power (Global), PADD III 2006 and 2015**

| | 2006 | 2015 |
|---|---|---|
| **Emissions Allocated** | Coke vs. Coal | Coke vs. NG |
| To gasoline, gm/MMBtu of gasoline | | |
| $SO_X$ | 1.391 | 4.852 |
| $NO_X$ | -0.362 | 1.378 |
| $CO_2$ | 43.4 | 424.0 |
| To diesel, gm/MMBtu of diesel | | |
| $SO_X$ | 0.426 | 1.756 |
| $NO_X$ | -0.111 | 0.499 |
| $CO_2$ | 13.3 | 153.4 |

**Table 5-14 Coke-to-Cement (Global), PADD III 2006 and 2015**

| | 2006 | 2015 |
|---|---|---|
| **Emissions Allocated** | Coke vs. Coal | Coke vs. Coal |
| To gasoline, gm/MMBtu of gasoline | | |
| $SO_X$ | 2.236 | 2.766 |
| $NO_X$ | -0.908 | -1.123 |
| $CO_2$ | 126 | 155 |
| To diesel, gm/MMBtu of diesel | | |
| $SO_X$ | 0.684 | 1.001 |
| $NO_X$ | -0.278 | -0.406 |
| $CO_2$ | 38 | 56 |

## CFE Background Data: Resid – 2006 and 2015 net changes by function

**Table 15 Heavy Residual Oil-to-Power/Heat vs. Natural Gas-to-Power/Heat, PADD III 2006**

| Emissions Allocated | Electric Utilities | Industrial | Commercial | Total |
|---|---|---|---|---|
| To gasoline, gm/MMBtu of gasoline | | | | |
| $SO_X$ | 7.226 | 10.608 | 4.420 | 22.254 |
| $NO_X$ | 0.999 | 0.058 | 0.047 | 1.104 |
| $CO_2$ | 1,833 | 186 | 77.1 | 2,097 |
| To diesel, gm/MMBtu of diesel | | | | |
| $SO_X$ | 2.211 | 3.246 | 1.352 | 6.809 |
| $NO_X$ | 0.306 | 0.018 | 0.014 | 0.338 |
| $CO_2$ | 561 | 57.1 | 23.6 | 642 |

**Table 16 Heavy Residual Oil-to-Power/Heat vs. Natural Gas-to-Power/Heat, PADD III 2015**

| Emissions Allocated | Electric Utilities | Industrial | Commercial | Total |
|---|---|---|---|---|
| To gasoline, gm/MMBtu of gasoline | | | | |
| $SO_X$ | 5.958 | 8.746 | 3.644 | 18.349 |
| $NO_X$ | 0.823 | 0.048 | 0.039 | 0.910 |
| $CO_2$ | 1,512 | 154 | 63.6 | 1,729 |
| To diesel, gm/MMBtu of diesel | | | | |
| $SO_X$ | 0.156 | 3.165 | 1.319 | 6.640 |
| $NO_X$ | 0.298 | 0.017 | 0.014 | 0.329 |
| $CO_2$ | 547 | 55.6 | 23.0 | 626 |