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Greenhouse Gas Index for Products in 39 Industrial Sectors: Petrochemicals

NAICS CODE 325110

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Important Note

This module is not a stand-alone document. Readers should refer to the introduction for a more detailed overview and discussion of the Framework and procedures to determine the GGI and, especially, to the ***Note on Common References, Default Values, Acronyms and Abbreviations used in the Modules***. Common information includes default values for CO_2 emissions from electricity and thermal energy derived from coal, oil and natural gas; a list of acronyms and abbreviations; guidance on using the sources cited for US exports, imports, and production by sector, and CO_2 emissions from electricity produced in nations that export to the United States.

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Contents

1. Introduction

The NAICS Code 325110, for petrochemicals, consists primarily of 15 products (listed in the next paragraph). During 2019, US exports of these products were about $4.1 billion, and imports were about $1.28 billion.[1] The US total production of such petrochemicals in 2018 was $58.9 billion.[2] In this module, we determine greenhouse gas indices (GGIs)—which track taxed GHG process emissions and the contribution of the carbon content of products derived from fossil resources along the supply and production chain in a manner analogous to that used in value-added taxes—for petrochemical products. When multiplied by the GHG tax, the result is the relevant export rebate or import charge. A minimum GGI of 0.50 tonnes CO_2e/tonne product is required for an export rebate or the imposition of an import charge.

The products covered in this module include ethane, butane, pentanes, ethylene, propylene, butadiene, butylene, isoprene, linear alpha olefins, benzene, toluene, mixed xylenes, ethyl benzene, styrene (from NAICS Code 325110); and propane (from NAICS 211130). GGIs are provided for all such products, except for linear alpha olefins, for which there is no single formula.

During the last several years, US production of ethane, propane, butane, and pentanes has increased because of the increased production of natural and associated gas. The manufacturing of ethylene and propylene have also increased because of the increased amount of their raw materials (ethane and propane) and related lower prices that became available as a result of hydraulic fracturing and horizontal drilling.

Petrochemical products are created by transforming ethane, propane, butane and one or more refined hydrocarbon feedstocks into new products through cracking and separation by distillation. Major contributors to the GGI for these products are feedstocks, commercial fuels used for thermal energy, and electricity. Feedstocks include natural gas liquids (NGLs), ethane, butane, naphtha, gas oil, pyrolysis gasoline, and reformate. The manufacturer will know or can determine from suppliers GGI values for purchased materials, fuels, and electricity. Since petrochemicals can be made using different feedstocks and processes, their GGIs and potential rebates or import charges will depend on the specific materials and the processes they employ. The GGIs for the various products in this module range from 3.0 tonnes CO_2e/tonne ethane separated from NGLs to 6.07 tonnes CO_2e/tonne styrene.

[1] *See*: **https://usatrade.census.gov/data/Perspective60/View/dispview.aspx**.
[2] *See*: **https://data.census.gov/cedsci/table?q=AM1831BASIC&tid=ASMAREA2017.AM1831BASIC01** for the AM1831BASIC01 Annual Survey of Manufactures: Summary Statistics for Industry Groups and Industries in the US: 2018–2020.

There are two major steps involved in determining GGI values for petrochemical products. The first is to evaluate the total input of taxed sources of GHG emissions—$CO_2e(TOT)$. The second is to allocate this total to the entire slate of covered products created by the manufacturer. Since petrochemicals are derived from produced fossil resources, we propose that allocation of total emissions to petrochemical products should be based on the fraction of carbon by weight in each product—*cf*, as described below (and in more detail in the introduction to the modules).

In the case of petrochemicals and derivatives thereof, determination of $CO_2e(TOT)$ is simplified because there are no fossil resources produced in the petrochemical process itself and, as defined in our Framework,[3] manufacturing petrochemicals generates no GHG emissions from untaxed sources. (Note that emissions of CO_2 do occur from the combustion of commercial fuels and, in some cases, combustion of a portion of the feedstock and products, but these were already taxed when they were created earlier in the supply chain.) Principal contributions to $CO_2e(TOT)$ occur from purchased feedstocks, electricity, and fuels used to create thermal energy.

The GGIs for products in the petrochemical sector are determined by allocating total taxed sources of GHG emissions, $CO_2e(TOT)$, to the total slate of covered products based on the carbon content, *cf*, by weight of each product. As described in the introduction to the modules, allocation by carbon content is based on first determining the average CO_2e emissions per tonne of carbon C, $<CO_2e/C>$,[4] in all products, and then allocating GHG emissions to products based on *cf*. $<CO_2e/C> = <CO_2e(TOT)/M(C)>$, where M(C) is the mass of carbon in all covered products. The manufacturer will know the composition and amounts of covered products they produce. So, for each product in this sector, the GGI is determined as follows:

$$GGI \quad = \quad <CO_2e/C>\ cf.$$

Note that in the event that the manufacturer produces only a single covered product, P, as is often the case for products in this module, GGI = $CO_2e(TOT)/M(P)$, where M(P) is the weight of the covered product (tonnes P). Allocation only requires specific treatment on a product-by-product basis when the process used by the manufacturer creates more than one covered product.

The discussion below provides a method for the Regulator to determine initial import charges based on publicly available information for covered GHG-intensive products. The discussion uses such information to indicate what export rebates and import

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[3] *See*: Flannery, Brian, Jennifer A. Hillman, Jan Mares, and Matthew C. Porterfield. 2020. *Framework Proposal for a US Upstream GHG Tax with WTO-Compliant Border Adjustments: 2020 Update*. Washington, DC: Resources for the Future. **https://www.rff.org/publications/reports/framework-proposal-us-upstream-ghg-tax-wto-compliant-border-adjustments-2020-update/**

[4] See the discussion in the introduction concerning the use of angle brackets “< >”to denote an average over the entire operation, e.g., a facility or entire sector, in this case to produce petrochemical products.

charges would be if there were an upstream GHG tax of $20 per tonne of CO_2e. This information would also be useful to the Regulator in evaluating the information provided by exporters to indicate their requested export rebate.

The major producers of petrochemicals are already obligated to annually determine and report to the US Environmental Protection Agency (EPA) their facility GHG emissions if they are over 25,000 tonnes per year. Thus, the firms in this sector will know the amount of the GHG emissions related to their petrochemical production. Under the Framework, suppliers would be required to communicate GGI values of their GHG-intensive products to their customers. Principal products from suppliers that contribute to $CO_2e(TOT)$ include feedstocks from oil or natural gas or their derivatives, commercial fuels used for thermal energy, and electricity. Here we use available public information for such products. More accurate and timely information to determine rebates and import charges could undoubtedly be obtained by the Regulator from either the industry association or firms (e.g., S&P Global) that have a business of obtaining and marketing information about the GHG aspects of various chemical products and corporate actions.

The overall average GHG emissions from fuels used to manufacture electricity in the relevant country should be used to determine the CO_2e emissions from electricity use associated with production of the imported petrochemical products unless more specific, verifiable information is provided to the Regulator.[5]

An important note: We emphasize that the estimates in this module are meant only to provide indicative, representative values for GGIs of petrochemical products. Some of the public data on which the calculations rely date back years and probably are not representative of industry performance today. Actual values will depend on determination of the GGIs for each specific product produced at a specific facility. Since companies, associations, and commercial firms that collect and market information about the energy and emissions profiles of various sectors and products can provide more accurate information than was used here, the Regulator should seek such information when determining potential import charges or evaluating requests for export rebates. The estimates here do not account for all chemicals or other raw materials that may have incurred the GHG tax directly or indirectly. Subject to the administrative costs to evaluate all such inputs and be consistent for both export rebates and import charges, the Regulator should strive to accept all verifiable raw material inputs to the GGI for specific products.

[5] Such electricity information can be found in IEA's *World Energy Balances 2020*; **https://www.iea.org/subscribe-to-data-services/world-energy-balances-and-statistics**.

2. Ethane

The following analysis would help the Regulator evaluate requests for rebates for ethane exports. Ethane is predominantly derived from natural gas liquids (NGLs), produced either with natural gas or crude oil. The NGLs are then separated into ethane, propane, butane, and pentanes and/or natural gasoline. This analysis assumes that the vast majority of ethane is derived from NGLs that are derived either from the production of crude oil or natural gas.[6] This analysis assumes the current average energy to separate NGLs is Manley's more optimum result (see footnote 6), which is 0.0859 MBtu/NGL barrel. A typical mix of products within NGL is ethane (42 percent), propane (28 percent), butanes (17 percent), and pentanes/natural gasoline (13 percent).[7] The density of NGL components varies from 4.76 to 5.20 lbs per gallon.[8] Here we use 5.00 lbs/gallon, which results in 210 lbs/barrel. We estimate $CO_2e(TOT)$ for ethane based on its carbon content and the energy required to distill and separate it from NGLs.

Assuming that natural gas is used to provide the separation energy, the GGI for NGL would be (0.0859 MBtu/NGL BBL) (1,000 cubic feet natural gas/MBtu) (0.05 lb natural gas/cubic foot natural gas) (1 tonne natural gas/2,200 lbs gas) (44 tonnes CO_2/16 tonnes natural gas) (1 BBL NGL/210 lbs NGL) (2,200 lbs NGL/tonne NGL) = 0.056 tonnes CO_2e/tonne NGL. Since more energy is required to cool and separate ethane than propane (which requires more than butanes, which in turn require more than pentanes), a simple means of reflecting this is needed. Until more information is available, one can assume that the energy to separate ethane from NGLs is 30 percent more than to separate the above average; propane will require 10 percent more energy than the above average; butanes will require 10 percent less energy than the above average; and pentanes will require 30 percent less energy than the above average. Thus, the GGIs for separation of ethane would be as follows:

- (1.3) (0.056 tonnes CO_2e/tonne NGL) = 0.073 tonnes CO_2e/tonne ethane;
- for propane, the separation GGI would be (1.1) (0.56 tonnes CO_2e/tonne NGL) = 0.062 tonnes CO_2e/tonne propane;
- for butanes, the separation GGI would be (0.9) (0.56 tonnes CO_2e/tonne NGL) = 0.05 tonnes CO_2e/tonne butanes; and

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[6] We use estimates of the energy to separate the NGLs from Manley, D.B. 1998. "Thermodynamically Efficient Distillation: NGL Fractionation." *Latin American Applied Research*. Manley estimates the energy to separate NGL into its constituents by processes used then and by a more economically optimum process that is closer to thermodynamic efficiency.

[7] *See*: **https://www.eia.gov/conference/ngl_virtual/eia-ngl_workshop-anne-keller.pdf**, Markets Overview NGL USA, Page 17.

[8] *See*: **https://coolconversion.com/density-volume-mass/**

- for pentanes, the separation GGI would be (0.7) (0.56 tonnes CO_2e/tonne NGL) = 0.04 tonnes CO_2e/tonne pentanes.

Accounting for its carbon content and emissions from energy use, the GGI is determined as follows:

GGI	=	CO2e(TOT)/tonne ethane;
	=	0.073 tonnes CO2e/tonne ethane + 88 tonnes CO2e/30 tonnes ethane
	=	(0.073 + 2.93) tonnes CO2e/tonne ethane
	=	3.00 tonnes CO2e/tonne ethane.

2.1. Export Rebates

According to US Trade Online data for organic chemicals, in 2020, $1.07 billion worth of ethane was exported from the United States.[9] If there is a GHG tax of $20 per tonne of CO_2, the export rebate for ethane separated from NGLs would be $60.00 per tonne.

2.2. Import Charges

In 2016, the US Energy Information Administration (EIA) indicated that essentially no ethane was imported into the United States.[10] If there were an upstream GHG tax of $20 per tonne of CO_2, the import charge for the ethane would be $60.00 per tonne.

[9] *See*: **https://usatrade.census.gov/data/Perspective60/Dim/dimension.aspx?ReportId=38.**
[10] *See*: “Petroleum and Other Liquids Imports”; **https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MENIMUS2&f=A.**

3. Propane

The following analysis would help the Regulator evaluate requests for rebates for propane. Because propane is so similar in its sources to ethane and butanes, we include discussion of propane in this module with products in NAICS Code 325110, even though propane is actually listed in NAICS Code 211130 (Natural Gas Extraction).

Propane is predominantly derived from NGLs produced either with natural gas or crude oil. The NGLs are then separated into ethane, propane, butane, and pentanes and/or natural gasoline. This analysis assumes that the vast majority of propane is derived from NGLs that are derived either from the production of crude oil or natural gas. As described in the above section on ethane, the contribution to the GGI from the separation of propane from NGLs would be 0.062 tonnes CO_2e/tonne propane. The contribution to the GGI of propane from its carbon content is 132 tonnes CO_2/44 tonnes propane. So, for propane, the GGI is determined as follows:

$$\begin{aligned} GGI &= CO_2e(TOT)/\text{tonne propane}; \\ &= (0.062 + 3.0)\text{ tonnes } CO_2e/\text{tonne propane} \\ &= 3.06\text{ tonnes } CO_2e/\text{tonne propane}. \end{aligned}$$

3.1. Export Rebates

The United States exported about 1.2 million barrels of propane per day in 2020 according to EIA.[11] If there were a GHG tax of $20 per tonne of CO_2, the export rebate for propane separated from NGLs would be $61.20 per tonne.

3.2. Import Charges

In 2020, there were about 114,000 barrels per day of propane imported into the United States according to EIA. If there were an upstream GHG tax of $20 per tonne of CO_2, the import charge for the propane would be $61.20 per tonne.

[11] *See:* EIA "Petroleum and Other Liquids", for both the export and import figures: **https://www.eia.gov/dnav/pet/pet_move_impcus_d_nus_Z00_mbblpd_a.htm**;

4. Normal Butanes and Isobutanes

The following analysis would help the Regulator evaluate requests for rebates for butane exports. Butanes are derived from NGLs and from refinery processes, including crude oil distillation, catalytic cracking plus distillation, and others. About 90 percent of the butanes manufactured and/or separated in a refinery are used in the refinery to make finished, marketable products (e.g., gasoline). Thus, one can assume that butanes that are exported are derived from NGLs. As provided in the section on ethane, above, the contribution to the GGI from the separation of butanes from NGLs would be 0.050 tonnes CO_2e/tonne butanes. The contribution to the GGI of butanes from their carbon content is 176 tonnes CO_2/58 tonnes butanes. So, for butanes, the GGI is determined as follows:

$$
\begin{aligned}
GGI &= CO_2e(TOT)/\text{tonne butanes;} \\
&= (0.050 + 3.03) \text{ tonnes } CO_2e/\text{tonne butanes} \\
&= 3.08 \text{ tonnes } CO_2e/\text{tonne butanes.}
\end{aligned}
$$

4.1. Export Rebates

According to EIA (see footnote 11), there were about 357,000 barrels per day of normal butane exports from the United States in 2020. If there were a GHG tax of $20 per tonne of CO_2, the export rebate for butane separated from NGLs would be $61.60 per tonne butanes.

4.2. Import Charges

In 2020, there were about 26,000 barrels per day of normal butane imported into the United States according to EIA. If there were an upstream GHG tax of $20 per tonne of CO_2, the import charge for the butanes would be $61.60 per tonne butanes.

5. Pentanes Plus

Pentane, hexanes, and some heavier hydrocarbons are derived from natural gas and from refinery operations with the production from NGLs being about three times the amount produced in refineries. Their primary use is to make gasoline and related refinery products. However, these are commonly used as a blowing agent in the production of polystyrene foam, as a chemical solvent, and as a diluent for Canadian oil sands production. Imports of these products to the United States are a slight fraction of US exports. According to our above analysis for ethane, the GGI for pentane derived from NGLs is substantially less than that derived from refinery operations (see footnote 11). Thus, the pentanes can be assumed to be derived from the separation of NGLs for the purpose of determining its GGI.

As described in the above section on ethane, the contribution to GGI from separation of pentanes from NGLs would be 0.040 tonnes CO_2e/tonne pentanes. The contribution to the GGI of pentanes from its carbon content is 220 tonnes CO_2/72 tonnes pentane. So, for pentane, the GGI is determined as follows:

GGI	=	CO2e(TOT)/tonne pentane;
	=	(0.040 + 3.06) tonnes CO2e/tonne pentane
	=	3.10 tonnes CO2e/tonne pentane.

5.1. Export Rebates

According to EIA, there were about 192,000 barrels of pentanes plus exported from the United States in 2020 (see footnote 11). If there were a GHG tax of $20 per tonne of CO_2, the export rebate for pentane separated from NGLs would be $62.00 per tonne pentanes.

5.2. Import Charges

According to EIA, there were essentially zero barrels for pentanes plus imported into the United States in 2020 (see footnote 11). If there were an upstream GHG tax of $20 per tonne of CO_2, the import charge for pentanes would be $62.00 per tonne pentanes.

6. Ethylene

Ethylene is predominantly made by two processes—cracking of ethane and/or propane and cracking of naphtha. Some is made in the course of cracking processes in refineries, which is assumed to be small enough to disregard for initial determinations of the GGIs. The products from the cracking processes include increasing amounts of non-ethylene products, ranging from less than 20 percent to over 200 percent of ethylene produced—as the raw material changes from just ethane through propane to naphtha and gas oil. The determinations of GGIs for ethylene below also include determinations for other products from such cracking.

The producer of ethylene will be able to obtain the GGI for its raw material ethane, propane, naphtha, or other from the respective suppliers.

6.1. Cracking of Ethane

According to the 2006 Intergovernmental Panel on Climate Change's (IPCC's) Guidelines for National Greenhouse Gas Inventories, for ethylene made from ethane, 0.19 tonnes CO_2e/tonne product are generated from extra fuel used in the process.[12] In addition, such production requires 278 kWh/tonne high-value products.[13] High-value products are those listed in the following table.

The list of product amounts, carbon fraction (*cf*), carbon content, and GGIs are as follows:

Table 1. Product amounts, carbon fraction (*cf*), carbon content, and GGI

Product	Amount per kg product	Carbon fraction in product	Carbon content of product/kg all products	GGI tonnes CO_2e/tonne product
Ethylene	0.803	0.857	0.688	3.76
Propylene	0.016	0.857	0.014	3.76
Butadiene	0.023	0.889	0.020	3.89
Aromatics	0.0	0.92	0.0	0.0
Other C4	0.006	0.828	0.005	3.63
C5/C6	0.026	0.859	0.022	3.76
C7 + non-aromatics	0.0	0.84	0.0	0.0
Other products	0.0	0.844	0.0	0.0
Total	**0.874**		**0.749**	

[12] *See*: Tables 3.14 and 3.25 in Chapter 3 of the 2006 IPCC Guidelines; **https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/**.
[13] *See*: Table 2.6.1. in Worrell, Ernst, et al. 2007. World Best Practice Energy Intensity Values for Selected Industrial Sectors. LBNL–62806. Berkeley, CA: Lawrence Berkeley National Laboratory.

We determine the GGI for products derived from cracking ethane as follows. The GGI for ethane from Section 2 above is 3.00 tonnes CO_2e/tonne ethane. The CO_2e emissions per tonne of all products from the use of electricity based on natural gas would be (278 kWh/tonne high-value products) (0.87 high-value products/total products) (0.42 tonnes CO_2e/1,000 kWh) = 0.10 tonnes CO_2e/tonne products (see reference in footnote 13). In addition, fuel is required to crack ethane, which results in 0.19 tonnes CO_2e/tonne products (see reference in footnote 12).

CO_2e(TOT) per tonne of all products from cracking ethane is (3.00 + 0.10 + 0.19) tonnes CO_2e/tonne products, which equals 3.29 tonnes CO_2e/tonne all products. Consequently, the average <CO_2e/C> of emissions per tonne of C is determined as follows:

$$\begin{aligned} \langle CO2e/C \rangle &= (3.29 \text{ tonnes CO2e/tonne products})/(0.75 \text{ tonnes C/tonne products}) \\ &= 4.39 \text{ tonnes CO2e/tonne C.} \end{aligned}$$

Multiplying the average <CO_2e/C> by the carbon fraction *cf* in each product provides the GGI for the product. Thus, for example, the GGI for ethylene with *cf* = 0.857 tonnes C per tonne of ethylene based on ethane is as follows:

$$\begin{aligned} \text{GGI} &= \langle CO_2e/C \rangle\ cf; \\ &= (4.39 \text{ tonnes } CO_2e\text{/tonne C})\ (0.857 \text{ tonnes C/tonne ethylene}) \\ &= 3.76 \text{ tonnes } CO_2e\text{/tonne ethylene.} \end{aligned}$$

6.2. Cracking of Propane

For ethylene made from propane, extra fuel is not used in cracking propane (see reference in footnote 12). However, because electricity is required to crack both ethane and naphtha, it is assumed to be required for cracking propane in the same amount of 278 kWh/tonne of high-value products where high-value products are listed in the table below.

The list of product amounts, carbon fraction, carbon content *cf*, and GGIs are as follows:

Table 2. Cracking of propane: Product amounts, carbon fraction, carbon content, and GGI

Product	Amount per kg product	Carbon fraction in product	Carbon content of product/kg all products	GGI tonnes CO_2e/tonne product
Ethylene	0.465	0.857	0.398	4.40
Propylene	0.125	0.857	0.107	4.40
Butadiene	0.048	0.889	0.043	4.56
Aromatics	0.0	0.92	0.0	0.0
Other C4	0.012	0.828	0.010	4.25
C5/C6	0.063	0.859	0.054	4.41
C7 + non-aromatics	0.0	0.84	0.0	0.0
Other products	0.0	0.844	0.0	0.0
Total	0.713		0.612	

We determine the GGI for products derived from cracking propane as follows. The GGI for propane in Section C above is 3.06 tonnes CO_2e/tonne propane. The CO_2e emissions per tonne of all products from the use of electricity based on natural gas are assumed to be the same as for cracking ethane—and thus would be (278 kWh/tonne high-value products) (0.71 high-value products/total products) (0.42 tonnes CO_2e/1,000 kWh) = 0.083 tonnes CO_2e/tonne products. Extra fuel is not required to crack propane.[14]

Thus, CO_2e(TOT) per tonne of all products from cracking propane is 3.06 tonnes CO_2e/tonne products + (0.083 tonnes CO_2e/tonne products) = 3.14 tonnes CO_2e/tonne all products. Consequently, the average $<CO_2e/C>$ of emissions per tonne of C is determined as follows:

$$\begin{aligned} <CO_2e/C> &= (3.14 \text{ tonnes } CO_2e/\text{tonne products})/(0.612 \text{ tonnes C/tonne product}) \\ &= 5.13 \text{ tonnes } CO_2e/\text{tonne C}. \end{aligned}$$

Multiplying the average $<CO_2e/C>$ by the carbon fraction, *cf*, in each product provides the GGI for the product. Thus, the GGI for ethylene with *cf* = 0.857 tonnes C per tonne of ethylene based on propane is as follows:

$$\begin{aligned} \text{GGI} &= <CO_2e/C>\, cf; \\ &= (5.13 \text{ tonnes } CO_2e/\text{tonnes C})\ (0.857 \text{ tonnes C/tonne ethylene}) \\ &= 4.40 \text{ tonnes } CO_2e/\text{tonne ethylene}. \end{aligned}$$

[14] See reference in footnote 12.

6.3. Cracking of Naphtha

For ethylene made from naphtha, extra fuel is not used in cracking naphtha (see reference in footnote 12). In addition, 278 kWh/tonne of high-value products are required by such production, where high-value products are listed in the table below.

The list of product amounts, carbon fraction (*cf*), carbon content, and GGIs are as follows:

Table 3. Cracking of Naphtha: Product amounts, carbon fraction, carbon content, and GGI

Product	Amount per kg product	Carbon fraction in product	Carbon content of product/kg all products	GGI tonnes CO_2e/ tonne product
Ethylene	0.324	0.857	0.278	4.43
Propylene	0.168	0.857	0.144	4.43
Butadiene	0.05	0.889	0.044	4.59
Aromatics	0.104	0.92	0.095	4.75
Other C4	0.062	0.828	0.051	4.27
C5/C6	0.040	0.859	0.033	4.43
C7 + non-aromatics	0.012	0.84	0.010	4.33
Other products	0.086	0.844	0.073	4.36
Total	**0.845**		**0.728**	

We determine the GGI for products derived from cracking naphtha as follows. The GGI for naphtha is 3.66 tonnes CO_2e/tonne naphtha as determined in our module on refined petroleum products. The CO_2e emissions per tonne of all products from use of electricity based on natural gas would be (278 kWh/tonne high-value products) (0.845 tonnes high-value products/tonne of total products) (0.42 tonnes CO_2e/1,000 kWh) = 0.10 tonnes CO_2e/tonne all products. Thus, CO_2e(TOT) per tonne of all products from cracking naphtha is (3.66 + 0.10) tonnes CO_2e/tonne products = 3.76 tonnes CO_2e/tonne all products. Consequently, the average $\langle CO_2e/C \rangle$ of emissions per tonne of C is determined as follows:

$$\langle CO_2e/C \rangle = (3.76 \text{ tonnes } CO_2e/\text{tonne of all products}) / (0.728 \text{ tonnes C/ tonne of all products})$$
$$= 5.16 \text{ tonnes } CO_2e \text{ per tonne C.}$$

Multiplying the average <CO_2e/C> in all products by the carbon fraction (*cf*) in each product provides the GGI for the product. Thus, the GGI for ethylene with *cf* = 0.857 tonnes C per tonne of ethylene based on naphtha is as follows:

$$
\begin{aligned}
\text{GGI} &= \langle \text{CO2e/C} \rangle \text{ cf;} \\
&= \text{(5.16 tonnes CO2e/tonne C) (0.857 tonnes C tonne ethylene)} \\
&= \text{4.43 tonnes CO2e/tonne ethylene.}
\end{aligned}
$$

6.4. Export Rebates

According to US Trade Online data for organic chemicals, the United States exported about 376,000 tonnes of ethylene in 2020.[15] If there were an upstream GHG tax of $20 per tonne of CO_2, the rebate per tonne of ethylene made from ethane would be $75.20; from propane would be $88.00; and from naphtha would be $88.60.

6.5. Import Charges

According to US Trade Online data for organic chemicals, ethylene imports to the United States in 2020 were very slight—less than $100,000 worth. Until the exporter provides its information about the GGI for its exported ethylene, the Regulator should assume that the imported ethylene was made from naphtha. In such case, if there were an upstream GHG tax of $20 per tonne of CO_2, the import charges per tonne of ethylene made from naphtha would be $88.60.

Exporters of ethylene to the United States need to report to the Regulator whether they use ethane, propane, or naphtha (or another raw material) in their ethylene manufacture. If the imported ethylene is made from a raw material other than ethane, propane, or naphtha, the Regulator will determine the import charge based on the raw material used and factors provided in the sources listed above in footnotes 12 and 13.

[15] *See*: For both export and import figures, **https://usatrade.census.gov/data/Perspective60/Dim/dimension.aspx?ReportId=38.**

7. Propylene

Propylene is predominantly made by three processes: cracking of ethane and/or propane (2–12 percent), cracking of naphtha (17 percent), and propane dehydrogenation (85 percent). Some is also made in the cracking processes in refineries, which is assumed to be small enough to disregard for initial GGI determinations. Producers of propylene will be able to obtain the GGIs for their raw material ethane, propane, or naphtha from the relevant suppliers.

As provided in Section 3 above for propane, the GGI for propane is 3.06 tonnes CO_2e/tonne propane. And as provided in Section 6 for ethylene, the GGI for propylene derived from propane is 4.40 tonnes CO_2e/tonne propylene and the GGI for propylene derived from naphtha is 4.43 tonnes CO_2e/tonne propylene.

The GGI for propylene derived from propane dehydrogenation is based on the energy required to separate the propane from NGLs, plus an assumed amount of energy to perform the dehydrogenation process and the carbon embodied in the propylene. The assumed GGI value associated with energy required for the dehydrogenation process is 0.50 tonnes CO_2e/tonne propylene and the assumed dehydrogenation efficiency is 95 percent. The propane had a GGI of 3.06 tonnes CO_2e/tonne propane. Thus, for propylene from propane dehydrogenation, the GGI is determined as follows:

$$
\begin{aligned}
\text{GGI} &= \text{CO}_2\text{e(TOT)/tonne propylene;} \\
&= 0.50 \text{ tonnes CO}_2\text{e/tonne propylene} \\
&\quad + \text{(1 tonne propane/0.95 tonnes propylene) (3.06 tonnes CO}_2\text{e/tonne propane)} \\
&= \text{(0.50 + 3.22) tonnes CO}_2\text{e/tonne of propylene} \\
\text{GGI} &= 3.72 \text{ tonnes CO}_2\text{e/tonne propylene.}
\end{aligned}
$$

7.1. Export Rebates

According to US Trade Online data on organic chemicals, propylene exports in 2020 were $732 million.[16] If there were an upstream GHG tax of $20 per tonne of CO_2, the export rebate per tonne of propylene made from propane would be $88.00; the rebate for propylene made from naphtha would be $88.60/tonne; and the rebate for propylene made by the dehydrogenation process would be $74.40/tonne.

7.2. Import Charges

For 2020, US Trade Online data on organic chemicals indicated that propylene imports to the United States were about $134 million. Exporters of propylene to the United States need to report to the Regulator whether they use propane, naphtha, or

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[16] *See*: For both export and import figures, **https://usatrade.census.gov/data/Perspective60/Dim/dimension.aspx?ReportId=38.**

another raw material in their propylene manufacture and whether they used a cracking or propane dehydrogenation process. If the imported propylene is made from a raw material other than propane or naphtha, the Regulator will determine the import charge based on the raw material used—based on factors provided in the sources listed above in footnotes 12 and 13.

If the GHG tax were \$20 per tonne CO_2, the import charge for propylene would be \$88.00 per tonne if propane was used as its raw material; \$88.60 per tonne if naphtha was used as its raw material; and \$74.40 per tonne if propane dehydrogenation is used to make the propylene.

8. Butadiene

Butadiene is produced commercially by three processes: steam cracking of naphtha, ethane, propane, and gas oils; catalytic dehydrogenation of n-butane and n-butene (i.e., the Houdry process); and oxidative dehydrogenation of n-butene. The vast majority of the world's butadiene is produced by the steam cracking process, with smaller amounts produced in the United States by oxidative dehydrogenation of n-butene. The steam cracking process produces varying amounts of butadiene depending on the raw material and cracking conditions.

The producer of butadiene will be able to obtain the GGIs for its raw material ethane, propane, naphtha, or gas oil from its suppliers. As provided in Section 6 above on ethylene, the GGI for butadiene based on naphtha is 4.59 tonnes CO_2e/tonne butadiene.

8.1. Export Rebates

US Trade Online data on organic chemicals reports that in 2020 there were $28 million worth of butadiene exports.[17] If there were an upstream GHG tax of $20 per tonne of CO_2, the export rebate for butadiene made from naphtha would be $91.80 per tonne.

8.2. Import Charges

US Trade Online data on organic chemicals reports that in 2020 there were $128 million worth of butadiene imports into the United States. They can be assumed to be made by the same processes as in the United States. If there were an upstream GHG tax of $20 per tonne of CO_2, the import charge for butadiene made from naphtha would be $91.80 per tonne.

[17] *See*: For both export and import figures, **https://usatrade.census.gov/data/Perspective60/Dim/dimension.aspx?ReportId=38.**

9. Butenes

Butenes (also known as butylenes) are produced in refineries primarily from the fluid catalytic cracking (FCC) unit; they are also produced in steam crackers that process naphtha or gas oil to make ethylene. As the information about the energy needed to produce butenes in an FCC unit is not available, there are sufficient similarities to its separation in steam cracking to use that information.

Producers of butenes will be able to obtain the GGI for their raw material naphtha or gas oil from their suppliers. In our module on refined petroleum products, we determine that the GGI for naphtha is 3.66 tonnes CO_2e/tonne naphtha.

As provided in Section 6, above, on ethylene, the GGI for "other C4" from cracking of naphtha (which are predominantly butenes) is 4.27 tonnes CO_2e/tonne butenes.

The butanes/butenes mixture produced by the steam cracker must be separated into butenes. This is not a simple distillation but an extractive distillation. Information about the CO_2e emissions from that step are not currently available. Thus, this analysis assumes that such separation of butylenes from butane would result in a substantially greater CO_2e value (i.e., 0.20 tonnes CO_2e/tonne butenes) than for the separation of NGLs as provided in Section 2 on ethane above.

GGI	=	CO_2e(TOT)/tonne butenes;
	=	0.20 tonnes CO_2e/tonne butene + 4.27 tonnes CO_2e/tonne butenes
GGI	=	4.47 CO_2e(TOT) per tonne butene.

9.1. Export Rebates

According to US Trade Online data on organic chemicals, there were about $132 million worth of exports of butenes in 2020.[18] If there were an upstream GHG tax of $20 per tonne of CO_2, the export rebate for butenes made from naphtha would be $89.40 per tonne.

9.2. Import Charges

According to US Trade Online data on organic chemicals, there were less than $1 million worth of imports of butenes into the United States in 2020. They can be assumed to be made by the same processes as in the United States. If there were an upstream GHG tax of $20 per tonne of CO_2, the import charge for butenes made from naphtha would be $89.40 per tonne.

[18] *See*: For both export and import figures, **https://usatrade.census.gov/data/Perspective60/Dim/dimension.aspx?ReportId=38.**

10. Isoprene

Isoprene, or 2-methyl-1,3-butadiene, can be produced by many different processes but appears to be predominantly produced as a C5 byproduct of the thermal cracking of naphtha or gas oil in the manufacture of ethylene and other olefins. That C5 product stream can be separated in a two-stage distillation process to isoprene. Thus, the GGI for isoprene has contributions from the manufacture of naphtha or gas oil, the steam cracking of them to make ethylene and the C5 fraction with isoprene, separation of the isoprene from other components of the C5 fraction, and the carbon contained in isoprene itself.

The producer of isoprene will be able to obtain the GGI for its raw material naphtha or gas oil from the relevant suppliers.

As determined in Section 6 on ethylene, the GGI for "C5/C6" (including isoprene) was 4.43 tonnes CO_2e/tonne C5/C6 based on naphtha.

The mixed C5s are separated in a two-stage distillation process into isoprene. Until more information is available, we assume that the energy to separate the C5 stream into isoprene is 0.20 tonnes CO_2e/tonne isoprene, which is substantially greater than the energy and related emissions to separate natural gas liquids into ethane through to pentanes. Thus, for isoprene, the GGI is determined as follows:

GGI = CO_2e(TOT)/tonne isoprene;
= 4.43 tonnes CO_2e/tonne isoprene + 0.20 tonnes CO_2e/tonne isoprene
= 4.63 tonnes CO_2e/tonne isoprene.

10.1. Export Rebates

According to US Trade Online data on organic chemicals, there were $3 million of isoprene exports from the United States in 2020.[19] If there were an upstream GHG tax of $20 per tonne of CO_2, the export rebate per tonne of isoprene derived from naphtha would be $92.60.

10.2. Import Charges

According to US Trade Online data on organic chemicals, there were $76 million of imports of isoprene into the United States in 2020. If there are imports of isoprene into the United States, the import charges for the products should be based on the assumption that the isoprene is derived from naphtha. Thus, if there were an upstream GHG tax of $20 per tonne of CO_2, the import charge per tonne of isoprene based on naphtha would be $92.60.

[19] *See*: For both export and import figures, **https://usatrade.census.gov/data/Perspective60/Dim/dimension.aspx?ReportId=38.**

11. Linear Alpha Olefins

Linear alpha olefins are straight-chain hydrocarbons with a double bond at the primary or alpha position. There are a wide range of these products C4 to C30 and higher. Industrially, they are commonly manufactured by two main routes: oligomerization of ethylene and Fischer-Tropsch synthesis followed by purification. The oligomerization process seems to be the primary one used in the United States.

The GGI for linear alpha olefins would be based on three factors: the CO_2e emissions from production of the ethylene raw material; the emissions caused by the oligomerization process for the particular product; and the carbon content of the product.

The Fischer-Tropsch process creates hydrogen and carbon monoxide from coal or natural gas. Those products are then catalytically converted to multiple hydrocarbons, including linear alpha olefins, which are separated from the mixed products. The GGI for these linear alpha olefins would be based on the CO_2e emissions caused by the Fischer-Tropsch process, the conversion and separation processes, and finally the carbon content of the product.

Without knowing the specific formula of the linear alpha olefins being exported or imported, it is not possible to determine a GGI for such products or the export rebate or import charge assuming a particular upstream GHG tax.

11.1. Export Rebates

Exporters of linear alpha olefins will be required to provide to the Regulator the concentration, identity, and raw materials for the various olefins in their exported product mix as well as and the GGI for them in order for the rebate to be computed.

11.2. Import Charges

Since linear alpha olefins can have from 4 to 30 or more carbon atoms, it is not feasible to have an import charge that would appropriately fit all such imported products. Thus, the Regulator should require any importer of linear alpha olefins to provide verifiable information about the concentration and identity of the various olefins as well as raw material for the olefins in their imported product mix, the process used to make such mix, and the GGI for such mix.

12. Benzene

Benzene is primarily made in refineries from pyrolysis gasoline (pygas) or from the product of a catalytic reformer. This catalytic operation converts essentially straight-chain hydrocarbons into cyclic hydrocarbons like benzene, toluene, and xylene. The reformate that is not blended into gasoline is further separated into benzene, toluene, and xylene. Pyrolysis gasoline is the product of steam cracking of naphtha or paraffins. It can be separated into benzene, toluene, and xylene.

Pyrolysis gasoline produced from naphtha would not require additional fuel. The GGI of the raw material naphtha is estimated as 3.66 tonnes CO_2e/tonne naphtha in our module on refined petroleum products. We assume the efficiency of converting naphtha to benzene is 99 percent.

Since multiple useful products are generated, the emissions from naphtha cracking cannot all be attributed to the pyrolysis gasoline produced. According to Boulamanti and Moya Rivera, naphtha feedstock on a weight basis results in an output of pyrolysis gasoline of about 28 percent, of which benzene represents 23 percent; toluene 12 percent; C8 aromatics (e.g., xylenes) 12 percent; and other 53 percent.[20]

Table 57 in the report by Boulamanti and Moya Rivera provides energy consumption for the processes used to produce aromatics depending on whether the process is based on pyrolysis gasoline or reformate. That table indicates that for pyrolysis gasoline–based process, 1.47 GJ of fuel, 3.9 GJ of steam, and 15 kWh of electricity are required per tonne of aromatics (i.e., benzene, toluene, and C8 aromatics). For reformate, Table 57 (mentioned above) indicates 0.35 GJ of fuel, 3.45 GJ of steam, and 9.2 kWh of electricity.[21]

For pyrolysis gasoline based on natural gas for processing/electricity:

- (1.47 GJ/tonne aromatics + 3.9 GJ/tonne aromatics) (0.947 MBtu/GJ) (0.0532 tonnes CO_2e/MBtu) = 0.274 tonnes CO_2e/tonne aromatics;
- (15 kWh/tonne aromatics) (0.42 tonnes CO_2e/1,000 kWh) = 0.006 tonnes CO_2e/tonne aromatics.

[20] See Table 31 in Boulamanti, A., and J. Moya Rivera. 2017. Energy Efficiency and GHG Emissions: Prospective Scenarios for the Chemical and Petrochemical Industry. EUR 28471 EN. Luxembourg (Luxembourg): Publications Office of the European Union. JRC105767. **https://publications.jrc.ec.europa.eu/repository/handle/JRC105767**

[21] The distribution of aromatics from processing pyrolysis gasoline from naphtha is based on Table 31 of the Boulamanti and Moya Rivera report cited above, and for processing reformate it is based on Section 5.7.2 of the same report.

For reformate based on natural gas for processing/electricity:

- (0.35 GJ/tonne aromatics + 3.45 GJ/tonne aromatics) (0.947 MBtu/GJ) (.0532 tonnes CO_2e/MBtu) = 0.191 tonnes CO_2e/tonne aromatics;
- (9.2 kWh/tonne aromatics) (0.42 tonnes CO_2e/1,000 kWh) = 0.004 tonnes CO_2e/tonne aromatics.

Table 4. Information to determine GGI for products derived from pyrolysis gasoline

Product of pyrolysis gasoline	Amount per kg product	Carbon fraction in product	Carbon content of product/kg all products	GGI tonnes CO2e/tonne product
Benzene	0.23	0.92	0.211	5.25
Toluene	0.12	0.91	0.109	5.19
Xylenes	0.12	0.91	0.109	5.19
Other products	0.53	0.88 est.	0.466	___
Total	**1.0**		**0.895**	

We determine the GGI for products derived from pyrolysis gasoline as follows. From Section 6 above on ethylene, the GGI of benzene and other aromatics derived from cracking naphtha is 4.75 tonnes CO_2e/tonne naphtha. The CO_2e emissions per tonne to separate all products using electricity and steam produced from natural gas would be (0.274 tonnes CO_2e/tonne aromatics + 0.006 tonnes CO_2e/tonne aromatics) = 0.28 tonnes CO_2e/tonne aromatics.

CO_2e(TOT) per tonne of all products from cracking naphtha to pyrolysis gasoline and separating it into the products where there is a 99 percent conversion efficiency is (4.75 tonnes CO_2e/tonne products)/0.99 + (0.28 tonnes CO_2e/tonne aromatics) = 5.08 tonnes CO_2e/tonne products. The GGI for benzene is determined as follows:

$$\begin{aligned} \langle CO_2e/C \rangle &= (5.08 \text{ tonnes } CO_2e/\text{tonne products})/(0.895 \text{ tonnes C/tonne product}) \\ &= 5.70 \text{ tonnes } CO_2e/\text{tonne C.} \end{aligned}$$

Thus, for example, the GGI for benzene based on allocation by its carbon content (*cf* = 0.92) is as follows:

$$\begin{aligned} \text{GGI} &= \langle CO_2e/C \rangle\, cf = (5.70 \text{ tonnes } CO_2e/\text{tonne C})\ (0.92) \\ &= 5.25 \text{ tonnes } CO_2e/\text{tonne benzene.} \end{aligned}$$

Reformate typically contains 12–23 percent benzene, up to 30 percent toluene, and 23–48 percent xylene along with other products.[22] For this analysis, assume benzene is 17 percent, toluene is 15 percent, xylenes are 31 percent, and other products are 32 percent.

Table 5. Information to determine GGI for products derived from reformate

Product of reformate	Amount per kg product	Carbon fraction	Carbon content (kg)	GGI (CO_2e/tonne product)
Benzene	0.17	0.92	0.16	5.00
Toluene	0.15	0.91	0.14	4.94
Xylenes	0.36	0.91	0.33	4.94
Other	0.32	0.88 (est.)	0.28	___
Total	**1.0**		**0.91**	

We determine GGI for products derived from reformate as follows. The GGI for benzene and other aromatics from the cracking naphtha (using results from Section 6 on ethylene) is 4.75 tonnes CO_2e/tonne naphtha. The CO_2 emissions per tonne of all products from use of electricity and steam produced from natural gas would be 0.191 tonnes CO_2e/tonne aromatics + 0.004 tonnes CO_2e/tonne aromatics = 0.20 tonnes CO_2e/tonne aromatics.

CO_2e(TOT) per tonne of all products from separating reformate into the products where there is a 99 percent separation efficiency is (4.75 tonnes CO_2e/tonne products)/0.99 + (0.20 tonnes CO_2e/tonne aromatics) = 5.00 tonnes CO_2e/tonne products. Consequently, the average <CO_2e/C> is determined as follows:

<CO_2e/C> = (5.00 tonnes CO_2e/tonne products)/(0.91 tonnes C/tonne products)
= 5.49 tonnes CO_2e/tonne C.

Multiplying the average <CO_2e/C> by the carbon fraction *cf* in each product provides the GGI for the product. Thus, for example, the GGI for benzene based on reformate, *cf* = 0.91 tonnes, is as follows:

GGI = <CO_2e/C> *cf*;
= (5.49 tonnes CO_2e/tonne C) (0.91 tonnes C/tonne benzene)
= 5.00 tonnes CO_2e/tonne benzene.

[22] See Section 5.7.2 in Boulamanti, A., and J. Moya Rivera. 2017. Energy Efficiency and GHG Emissions: Prospective Scenarios for the Chemical and Petrochemical Industry. EUR 28471 EN. Luxembourg (Luxembourg): Publications Office of the European Union. JRC105767. **https://publications.jrc.ec.europa.eu/repository/handle/JRC105767**

13. Toluene

Toluene, like benzene, is used to make other chemicals or is a small part of gasoline. Toluene is primarily made in refineries from pyrolysis gasoline (pygas) or from the product of a catalytic reformer. These catalytic operations convert essentially straight-chain hydrocarbons into cyclic hydrocarbons like benzene, toluene, and xylene. The reformate that is not blended into gasoline is further separated into benzene, toluene, and xylene. Pyrolysis gasoline is the product of steam cracking of naphtha or paraffins. It can be separated into benzene, toluene, and xylene.

As determined in the above section on benzene, the GGI for toluene made from cracked naphtha is 5.19 tonnes CO_2e/tonne toluene, whereas from reformate it is 4.94 tonnes CO_2e/tonne toluene.

14. Mixed Xylenes

Xylenes, like benzene and toluene, are used to make other chemicals or are a small part of gasoline and are primarily made in refineries from pyrolysis gasoline (pygas) or from the product of a catalytic reformer. These catalytic operations convert essentially straight-chain hydrocarbons into cyclic hydrocarbons like benzene, toluene, and xylene. The reformate that is not blended into gasoline is further separated into benzene, toluene, and xylene. Pyrolysis gasoline is the product of steam cracking of naphtha or paraffins. It can be separated into benzene, toluene, and xylene.

As determined in the above section on benzene, the GGI for mixed xylenes made from cracked naphtha is 5.19 tonnes CO2e/tonne xylenes and from reformate is 4.94 tonnes CO2e/tonne xylenes.

15. Individual Xylenes

The separation of a xylene mixture into the three individual xylenes (ortho, meta, and para) is currently a very energy-intensive process because there is little difference in the boiling points of the three isomers. Several new processes for their separation with a significantly lower energy requirement are in varying stages of development. Until new, less energy-intensive processes are available, an estimate of the energy required to separate the xylene mixture is required. Since public estimates of such separation energy have not been found, an estimate of the energy required is necessary. Since current processes involve two steps (including one of distillation), this module assumes that the energy use for xylene separation results in 0.882 tonnes CO_2e/tonne xylenes, which is twice the emissions for separation of naphtha in crude distillation (which is 0.441 tonnes CO_2e/tonne naphtha, as described below).

The GGI of the raw material naphtha is based on the GGI of thermal energy to heat crude oil for distillation into naphtha and other hydrocarbon products. The specific heat of crude oil is 0.51 Btu/lb petroleum degree F. The crude has to be heated from about 20 degrees C to a range of 350 to 390 degrees C for crude distillation. Thus, the GGI for the energy used to heat the crude would be (0.51 Btu/lb petroleum degree) (1.8 degrees F/degree C) (2,200 lbs petroleum)/(tonne petroleum) (360 degrees C) (1,000 cubic feet gas/MBtu) (0.05 lbs gas/cubic foot gas) (1 tonne gas/2,200 lbs gas) (44 tonnes CO_2/16 tonnes gas)—which results in a GGI of 0.441 tonnes CO_2e/tonne petroleum. Since the petroleum is separated into its constituent parts, its process-related GGI from thermal energy to produce naphtha, distillate, other distillation products, and hydrocarbon products derived from these parts, is 0.441 tonnes CO_2e/tonne naphtha.

Total taxed sources of GHG emissions, CO_2e(TOT) per tonne of xylenes, are 0.882 tonnes CO_2e/tonne xylenes + 5.19 tonnes CO_2e/tonne xylenes from pyrolysis gasoline = 6.07 tonnes CO_2e/tonne xylenes. So, for xylenes made from naphtha the GGI is determined as follows:

GGI = CO_2e(TOT)/tonne xylenes;
= 6.07 tonnes CO_2e/tonne xylenes.

Since xylenes are also made from reformate, CO_2e(TOT) per tonne based on reformate is 0.882 tonnes CO_2e/tonne xylenes + 4.94 tonnes CO_2e/tonne xylenes from reformate = 5.82 tonne xylenes from reformate. So, for xylenes made from reformate, the GGI is determined as follows:

GGI = CO2e(TOT)/tonne reformate;
= 5.82 tonnes CO2e/tonne xylenes.

15.1. Export Rebates

According to US Trade Online data on organic chemicals, in 2020 the exports included \$37 million worth of benzene, \$37 million of toluene, \$48 million of ortho xylene, \$46 million of meta xylene, and \$656 million of para xylene.[23] If there is a GHG tax of \$20 per tonne of CO_2, the export rebates for benzene; toluene; mixed xylenes; and ortho, meta, and para xylenes separated from pyrolysis gasoline or reformate are as follows:

Table 6. Export rebates under a GHG tax of \$20 per tonne CO_2e

Product	Process	GGI	Rebate/tonne Product
Benzene	pyrolysis gasoline	5.25 tonnes CO_2e/tonne benzene from pyrolysis gasoline	\$105.00
	Reformate	5.00 tonnes CO_2e/tonne benzene from catalytic reformer	\$100.00
Toluene	pyrolysis gasoline	5.19 tonnes CO_2e/tonne toluene from pyrolysis gasoline	\$103.80
	catalytic reformer	4.94 tonnes CO_2e/tonne toluene from catalytic reformer	\$98.80
Mixed xylenes	pyrolysis gasoline	5.19 tonnes CO_2e/tonne xylenes from pyrolysis gasoline	\$103.80
	catalytic reformer	4.94 tonnes CO_2e/tonne xylenes from catalytic reformer	\$98.80
Ortho, meta, and para xylenes	pyrolysis gasoline	6.07 tonnes CO_2e/tonne individ. xylene from pyrolysis gas	\$121.40
	catalytic reformer	5.82 tonnes CO_2e/tonne individ. xylene from cat. reform.	\$116.40

15.2. Import Charges

According to US Trade Online data on organic chemicals, in 2020 the United States imports were \$626 million worth of benzene, \$121 million of toluene, \$16 million of ortho xylene, \$3 million of meta xylene, and \$497 million of para xylene.

The analysis above for determination of the export rebates was based on data for European production. The GGIs determined above can therefore be used for imports from all countries until more product- and country-specific information is available. Thus, if there were an upstream GHG tax of \$20 per tonne of CO_2, the import charge for benzene; toluene; mixed xylene; and ortho, meta and para xylene imports would be as follows in the table below:

[23] *See*: For both export and import figures, **https://usatrade.census.gov/data/Perspective60/Dim/dimension.aspx?ReportId=38.**

Until the exporter provides verifiable information to the Regulator about its process to make the imported benzene, toluene, or xylene, the Regulator shall use the GGIs determined for use of the pyrolysis gasoline.

Table 7. Import charge under a GHG tax of \$20 per tonne CO_2e

Product	Process	GGI	Import Charge/tonne
Benzene	pyrolysis gasoline	5.25 tonnes CO_2e/tonne benzene from pyrolysis gasoline	\$105.00
	Reformate	5.00 tonnes CO_2e/tonne benzene from catalytic reformer	\$100.00
Toluene	pyrolysis gasoline	5.19 tonnes CO_2e/tonne toluene from pyrolysis gasoline	\$103.80
	catalytic reformer	4.94 tonnes CO_2e/tonne toluene from catalytic reformer	\$98.80
Mixed xylenes	pyrolysis gasoline	5.19 tonnes CO_2e/tonne xylenes from pyrolysis gasoline	\$103.89
	catalytic reformer	4.94 tonnes CO_2e/tonne xylenes from catalytic reformer	\$98.80
Ortho, meta, and paraxylenes	pyrolysis gasoline	6.07 tonnes CO_2e/tonne individ. xylene from pyrolysis gas	\$121.40
	catalytic reformer	5.82 tonnes CO_2e/tonne individ. xylene from cat. reform.	\$116.40

16. Ethyl Benzene (EB)

Ethyl benzene (EB) is produced by alkylation of benzene with ethylene. Table 91 of the Boulamanti and Moya Rivera report (see footnote 20) provides usage factors for ethylene of 0.27 tonnes ethylene/tonne EB and 0.76 tonnes benzene/tonne EB.

The GGIs for benzene produced from naphtha, naphtha cracking, and pyrolysis gasoline processing are provided above and are 5.25 tonnes CO_2e/tonne benzene based on pyrolysis gasoline process and 5.0 tonnes CO_2e/tonne benzene based on catalytic reforming process.

As provided in the above analysis of ethylene, the GGI for ethylene made from ethane would be 3.76 tonnes CO_2e/tonne ethylene and for ethylene derived from naphtha cracking 4.43 tonnes CO_2e/tonne ethylene.

Because the GGIs for ethylene made from ethane and naphtha and for benzene made from pyrolysis gasoline or reformate are close, their averages will be used—5.13 tonnes CO_2e/tonne benzene and 4.10 tonnes CO_2e/tonne ethylene.

The energy consumption for ethyl benzene production (according to the Table 91 in the Boulamanti and Moya Rivera report; see footnote 20) is from: steam, 0.34–1.72 GJ/tonne; electricity, 25–32 kWh/tonne; and fuel, 1.95 GJ/tonne. Using averages of these rates, they result in the following components of the GGI for ethyl benzene production:

- Electricity: (28.5 kWh/tonne EB) (0.42 tonnes CO_2e/1,000 kWh) = 0.012 tonnes CO_2e/tonne EB;
- Steam and fuel: (1.03 GJ/tonne EB + 1.95 GJ/tonne EB) (0.947 MBtu/GJ) (1,000 kscuf gas/MBtu) (0.0532 tonnes CO_2e/MBtu) = 0.150 tonnes CO_2e/tonne EB.

The contribution to the GGI of EB from steam, electricity, and fuel is (0.012 + 0.150) tonnes CO_2e/tonne EB = 0.162 tonnes CO_2e/tonnes EB. So, the GGI is determined as follows:

GGI = CO_2e(TOT)/tonne EB;
= (0.162 tonnes CO_2e/tonne EB)
+ (0.27 tonnes ethylene/tonne EB) (4.10 tonnes CO_2e/tonne ethylene)
+ (0.76 tonnes benzene/tonne EB) (5.13 tonnes CO_2e/tonne benzene)
= 5.17 tonnes CO_2e/tonne EB.

16.1. Export Rebates

According to US Trade Online data on organic chemicals, exports of ethyl benzene in 2020 were $24 million.[24] If there is an upstream GHG tax of $20 per tonne CO_2, the export rebate for ethyl benzene would be ($20 per tonne CO_2) (5.17 tonnes CO_2e/tonne EB) = $103.40 per tonne EB.

16.2. Import Charges

According to US Trade Online data on organic chemicals, there were no imports of ethyl benzene in 2020. The analysis above for determination of the export rebate was based on data for European production. The GGIs determined above can therefore be used for imports from all countries until more product- and country-specific information is available. Thus, if there were an upstream GHG tax of $20 per tonne CO_2, the import charges for ethyl benzene would depend on the processes to make the ethylene and benzene raw materials—however, based on averages for the two raw materials, the import charge would be $103.40 per tonne EB.

[24] *See*: For both export and import figures, **https://usatrade.census.gov/data/Perspective60/Dim/dimension.aspx?ReportId=38.**

17. Styrene

Styrene is made by the dehydrogenation of ethyl benzene (EB). To produce a tonne of styrene, 1.04–1.17 tonnes of EB are required.[25] For purposes of this analysis, we assume 1.10 tonnes of EB to be required per tonne of styrene. The Boulamanti and Moya Rivera report (see footnote 20) also indicates that thermal energy and electricity requirements are in the range of 4.86–8.28 GJ/tonne styrene and 70–170 kWh/tonne styrene. This analysis assumes that 6.57 GJ and 120 kWh are required. Thus, contributions to the GGI of styrene for the dehydrogenation process would be as follows:

- Electricity: (120 kWh/tonne styrene) (0.42 tonnes CO_2e/1,000 kWh) = 0.050 tonnes CO_2e/tonne styrene;
- Steam and thermal fuel: (6.57 GJ/tonne styrene) (0.947 MBtu/GJ) (0.0532 tonnes CO_2e/MBtu) = 0.331 tonnes CO_2e/tonne styrene.

The contribution to the GGI for styrene of steam, electricity, and fuel is (0.050 + 0.331) tonnes CO_2e/tonne styrene = 0.381 tonnes CO_2e/tonne styrene. So, the GGI is determined as follows:

$$
\begin{aligned}
\text{GGI} &= \text{CO}_2\text{e(TOT)/tonne EB;} \\
&= \text{(0.381 tonnes CO}_2\text{e/tonne styrene)} \\
&\quad + \text{(1.10 tonnes EB/tonne styrene) (5.17 tonnes CO}_2\text{e/tonne EB)} \\
\text{GGI} &= \text{6.07 tonnes CO}_2\text{e/tonne styrene.}
\end{aligned}
$$

17.1. Export Rebates

According to US Trade Online data on organic chemicals, exports of styrene in 2020 were \$1.62 billion.[26] If there were an upstream GHG tax of \$20 per tonne CO_2, the export rebate per tonne of styrene would be (\$20/tonne CO_2) (6.07 tonnes CO_2e/tonne styrene) = \$121.40.

17.2. Import Charges

According to US Trade Online data on organic chemicals, imports of styrene in 2020 were \$388 million. The analysis above for determination of the GGI was based on European products. The GGIs determined above can therefore be used for imports

[25] See Table 92 in Boulamanti, A., and J. Moya Rivera. 2017. Energy Efficiency and GHG Emissions: Prospective Scenarios for the Chemical and Petrochemical Industry. EUR 28471 EN. Luxembourg (Luxembourg): Publications Office of the European Union. JRC105767. **https://publications.jrc.ec.europa.eu/repository/handle/JRC105767**

[26] *See*: For both export and import figures, **https://usatrade.census.gov/data/Perspective60/Dim/dimension.aspx?ReportId=38.**

from all countries until more product- and country-specific information is available. Thus, if there were an upstream GHG tax of $20 per tonne CO_2, the import charge per tonne of styrene would be $121.40.

18. Other Petrochemical Products

18.1. Export Rebates

There are other products within this NAICS code that will have GGIs of 0.50 tonnes CO_2e/tonne product or more. US producers of such products will be able to provide the Regulator verifiable information indicating the GGIs for their exported products and thereby be entitled to export rebates. Until such time as the exporter can provide such information to the Regulator, no rebate would be provided.

18.2. Import Charges

Until such time as the exporter to the United States and/or the importer in the United States provides verifiable information to the Regulator of the GGI for the imported products—or the Regulator determines a GGI for such product—an initial import charge should be established. That initial GGI would be the arithmetic average of the GGIs provided above for three of the more complicated products—namely, mixed xylenes, ethyl benzene, and styrene—because the more complicated products in NAICS Code 325110 are the ones for which indicative GGIs have not been provided above. Such average GGI is 5.43 tonnes CO_2e/tonne product.