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Article

Modelling variation in petroleum products' refining footprints

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Abstract

Energy-related greenhouse gas emissions dominate the carbon footprints of most product systems, and petroleum is one of the main types of energy sources. This is consumed as a variety of refined products – most notably diesel, petrol (gasoline) and jet fuel (kerosene). Refined product carbon footprints are of great importance to regulators, policymakers and environmental decision-makers. For instance, they are at the heart of legislation such as the European Union's Renewable Energy Directive or the United States' Renewable Fuels Standard. This study identified 14 datasets that report footprints for the same system, European petroleum refining. For the main refined products – diesel, petrol and jet fuel – footprints vary by at least a factor of three. For minor products, the variation is even greater. Five different organs of the European Commission have estimated refining footprints: for main products these are relatively harmonic; for minor products much less so. The footprint variation is due mainly to differing approaches to refinery modelling, especially regarding the rationale and methods applied to assign shares of the total burden from the petroleum refinery operation to the individual products. Given the economic/social importance of refined products, a better harmony of their footprints would be valuable to their users.

Key words

Petroleum refining carbon footprints, refining carbon footprints, refined product carbon footprints

1 Introduction

Petroleum products fuel much of modern life. Of all energy types, crude petroleum oil has the largest market share, accounting for 33% of global and 36% of European energy use. Second is natural gas, at 24% both globally and in Europe. (BP plc, 2020) Greenhouse gas (GHG) emissions from energy systems, in turn, drives the carbon footprints of most product systems. With some exceptions – say, in agriculture or halon applications – energy production and consumption account for the majority, if not the vast majority, of life-cycle emissions.

So, carbon footprints of crude oil are important. And footprints of its production show large variations, mainly because of regional differences in crude oil quality, extraction technologies and efficiencies. According to (Masnadi et al., 2018), production carbon intensities (CIs) have national averages that range from around 3-20 g CO_2e/MJ, spread around a global average of 10.3, whilst some individual oil fields have CIs as high as 50. (Jing et al., 2020) report national-average production CIs ranging from 3.3 g CO_2e/MJ in Denmark to 29.2 g in the Democratic Republic of Congo.

This variation in production has been recognised by regulators in the recent revisions of the European Union's Fuel Quality Directive (DG Energy European Commission, Exergia, E3M Lab, & COWI, 2015) (Malins, Galarza, Baral, Brandt, El-Houjeiri, et al., 2014) (Malins, Galarza, Baral, Brandt, & Howorth, 2014). As part of those analyses, the Marketable Crude Oil Name (MCON) system was used as the basis for oil sector pathways definition and 115 pathways of oil products were considered. The 2018 revision of the Fuel Quality Directive did not apply all 115 pathways, but for petrol and diesel it differentiated footprints for five generalised pathways: conventional crude; natural gas-to-liquid; coal-to-liquid; natural bitumen, and oil shale (European Commission, 2018, p 10). The US State of California's Air Resources Board (CARB) has also built this production-CI variation into its Low Carbon Fuel Standard (California Air Resources Board, 2020). Under LCFS, footprints of gasoline and diesel are added an additional burden for crude oil production (currently 12.26 g CO_2e/MJ), based on a 3-year-average of California petroleum supplies.

But what about refining? Unlike production, refining's CI-variety has not yet been incorporated into regulation. But it is recognisable and to some extent recognised – and as this study shows, it can be significant. In contrast to the variation in petroleum production footprints, which are caused by physical/operation variety, this paper shows that the variation in petroleum refining footprints is primarily due to differences in inventory modelling. Models of the same system – European refineries – come up with a variety of footprints for the same products.

2 Objective, materials and method

The aim of this study is chiefly to document the variety in reported carbon footprints for refining of refined products. To avoid complications possibly presented by variation in physical/operational differences, the analysis has been restricted to a single refining system – that of Europe (EU + EFTA). Similar analyses surely could be done for other regions: indeed, one was done of transport fuels in the USA (Unnasch, Riffel, Sanchez, & Waterland, 2011). However, its scope was from well-to-wheel and included biofuels, and its focus was more on methods of biofuel footprinting.

The method of the study was: desk research to identify published carbon footprints or carbon intensities of European refining (i.e. as industry averages)[1]; in some cases, analysis to extract the refining footprint from a larger well-to-tank footprint; followed by inspection; analysis; and discussion.

3 Results

Fourteen sources of refined product footprints were identified (Table 1). Two of these, from Eurobitume and the Joint Research Centre (JRC), are available in multiple allocation keys. Three of the studies – from Ecofys, DG Environment and the PRELIM consortium – present aggregated data for the well-to-tank phase, but without breaking out the refining step. There is some overlap of sources: JRC publishes its own footprints, with input from

[1] These datasets served as the main materials of the study.

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CONCAWE, and supplied the footprints to DG Energy; Sphera/Thinkstep has also published footprints and supplied them to DG Environment; and IFEU has contributed to the footprints used by the ecoinvent association and DG Climate.

Table 1: European refined product footprints, by source

Source	Partitioning	Allocation key	Reference and date
CONCAWE	Marginal (LP)	Mass	(CONCAWE, 2017, p 5)
Ecofys	Marginal	Energy	(Ecofys, 2014)
ecoinvent LCI database	Unit process	Energy	(ecoinvent 3, 2019, V 3.6)
ESU	Black box (no partitioning)	Energy	(ESU-Services, Jungbluth, Meili, & Wenzel, 2018)
Eurobitume	Unit process	-Economic -Subdivision of processes[2]	(Eurobitume, 2012) (Eurobitume, 2019)
European Commission, DG Climate	Unit process	Energy	(DG Climate, Ricardo Energy & Environment, E4tech, & IFEU - Institut für Energie und Umweltforschung, 2020)
European Commission, DG Energy	Marginal (LP)	Unclear	(Edwards, Larive, Mahieu, & Rounveirolles, 2007)
European Commission, DG Environment	Unit process	Appears to be energy	(thinkstep, 2019)
European Commission, Joint Research Centre	Marginal (LP)	-Energy/system expansion -Economic -Added value	(Moretti, Moro, Edwards, Rocco, & Colombo, 2017)
IFP	Marginal (LP)	Economic	(Babusiaux, 2003) (Babusiaux & Pierru, 2007) (Tehrani Nejad M, 2007) (Prieur & Tilagone, 2007)
Plastics Europe	Black box (no partitioning)	Mass	(PlasticsEurope & Boustead, 2005)
PRELIM consortium	Unit process	Energy	(Jing et al., 2020)
Sphera/Thinkstep	Unit process	Energy	(Sphera, IFP, & EUCAR, 2020)
Statoil	Unit process	Energy	(Furuholt, 1995)

Of this universe, 17 footprint datasets were discovered (Table 2). Five of these – three from JRC and two from Eurobitume – are the same dataset calculated with a different allocation key. So arguably there are only 12 datasets. Four of them – from DG Climate, Ecofys, DG Environment and PRELIM – have not broken out refining from well-to-tank footprints. Two of those do, however, give some detail. DG Climate reports that its refining footprints are "in line with CONCAWE model used in JEC for conventional crude chains" (DG Climate et al.,

[2] As defined in ISO standards and elsewhere, whereby a multi-product process is subdivided into multiple processes.

2020, p 294). The PRELIM consortium (Jing et al., 2020) reports a footprint range for all refined products of 1.7-12.3 g CO_2e/MJ.

Most sources cover only a limited set of the products that can be obtained from petroleum refineries, and instead focus on the main ones (diesel, petrol and jet fuel). Eurobitume and Plastics Europe cover only the refined products of direct interest to their organisations, respectively, bitumen and naphtha.

The datasets have been characterised both by partitioning and by allocation key (Table 1). It is observed that in many textual descriptions of the datasets, the distinction between partitioning and allocation is non-existent or unclear. For that matter, (ISO, 2006, Paragraph 3.17) conflates the two, saying that allocation is the same as partitioning. The authors' observation is that they are not the same. Partitioning is the way a life-cycle system is broken into parts. In the event, a refinery can be broken into parts, say, unit process parts or a marginal part (to produce an incremental barrel of some product). Or it can be not partitioned, as in the case of a black box. Allocation, by contrast, is the key by which the emissions or consumptions are distributed amongst each part's products, residues and wastes.

Table 2: Carbon footprint of refined petroleum products, by sources and allocation key (in grams of CO2e per MJ lower heating value)

Source	**Allocation key**	LPG	Petrol	Naphtha	Kerosene / jet	Diesel	Heating oil	Marine gasoil	Heavy Fuel oil	Bitumen	Pet coke	Lubes / Wax	Sulphur	Hydrogen	Fuel gas
CONCAWE	Mass	5.2	5.5	6-7	6.1	7.2	4.7	2.9	-3.7	-10.1	-25	14.1	-1.3		
ecoinvent	Energy	6.9	7.7	2.2	4.7	4.7	4.7		2.4	4.4	5.1	19.2	14.6	7.4	6.8
Ecofys	Energy	Results for refining only are not broken out.													
ESU	Energy	8.4	8.5	4.3	5.7	5.8	5.8		4.6	4.9	6.0				5.7
Eurobitume	Economic									0.93					
Eurobitume	Subdivision									0.47					
European Commission, DG Climate	Energy	"Findings in line with CONCAWE."													
European Commission, DG Energy			7.0	4.4		8.6									
European Commission, DG Environment	Energy	Results for refining only are not broken out.													
European Commission, Joint Research Centre	Energy and system expansion		5.8		6.1	7.2			-4.3		-24.8			122.9	
European Commission, Joint Research Centre	Economic		5.9		7.8	8.4			-17.4		-58.7			92	
European Commission, Joint Research Centre	Added value		6		7.9	10.3			-29.8		-80.4			57.7	
IFP[3]	Economic		2.7			0.8	0.3		0.4						
Plastics Europe	Mass			2.5											
PRELIM consortium	Energy	The volume-weighted average refining CI of all 343 crudes vary within 10.1–72.1 kgCO2e/bbl or 1.7–12.3 gCO2e/MJ.													
Sphera/Thinkstep	Energy		9.6		2.5	3.4			4.1						
Statoil	Energy		6			3.3									

[3] The footprint values come from (Babusiaux & Pierru, 2007, p 840, Table 7)

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4 Discussion

Refining carbon footprints reported for European refined petroleum products have a remarkable variation. Those reported by five different organs of the European Commission also vary, but not as much as the entire range of datasets. With the studies either departing from the same input data, or in several cases even building on each other (at least in part), the footprint variation is mainly due to differences in modelling approaches. Some of the variation is also likely due to differences in data collection and perhaps to reference years. The boundary between two products, diesel and heating oil, is also unclear.

4.1 Variation of refinery carbon footprint values

There is a large-small spread of footprint values reported for each of the refined products (Table 3). This includes the major refined products diesel, petrol and jet fuel (Figure 1) that account for two-thirds of European refinery output (FuelsEurope, 2019, p 13), which all have at least a factor of three between their largest and smallest values. It also applies to the non-primary products as well (Figure 2).

Table 3: Large-small spread of the reported footprints, for each refined product

Refined product	Footprint spread factor[4]
Heating oil	19.4
Hydrogen	16.6
Pet coke	14.4
Diesel	12.9
Heavy Fuel oil	7.4
Petrol	3.6
Kerosene/Jet	3.2
Bitumen	3.1
Naphtha	3.0
LPG	1.6
Lubes/Wax	1.4
Fuel gas	1.2
Sulphur	1.1
Marine gasoil	NA

Figure 1: Variation of the reported footprints, for primary products

[4] The quotient of the largest value divided by the smallest value, for that product. In the case of negative values, the spread factor is the absolute difference of the largest and smallest (most negative) divided by the largest (most positive).

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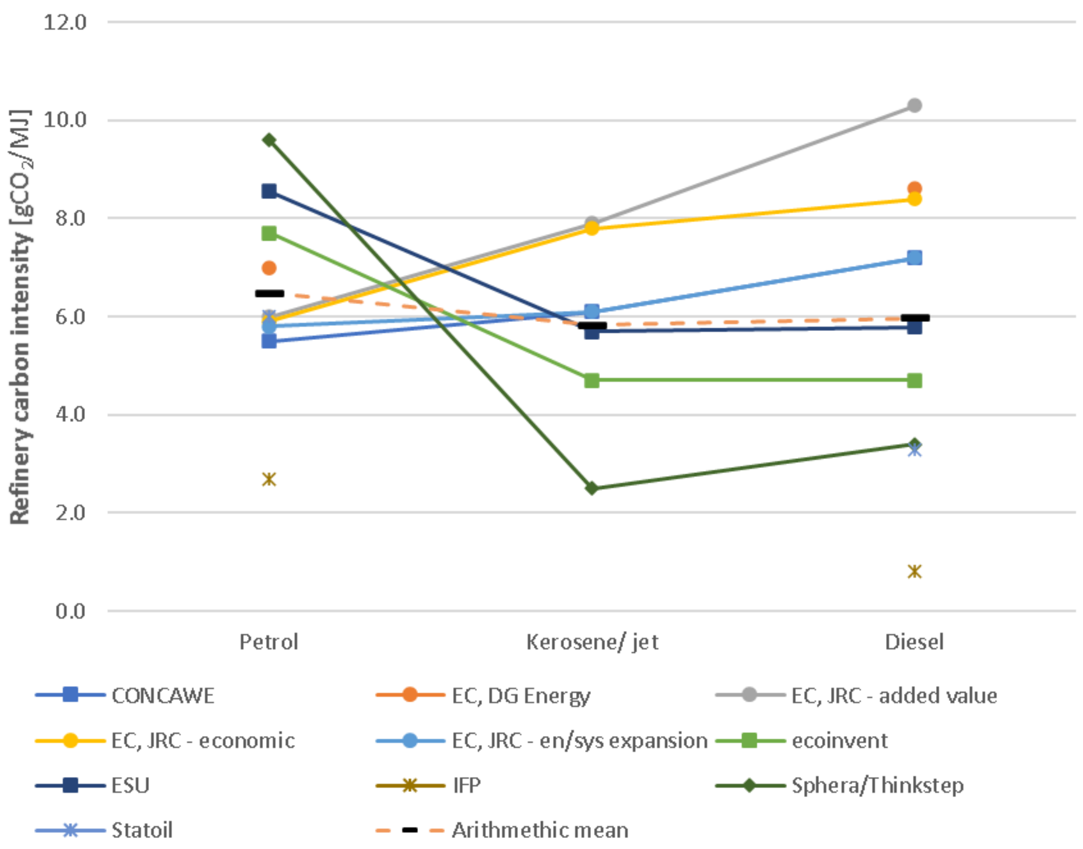
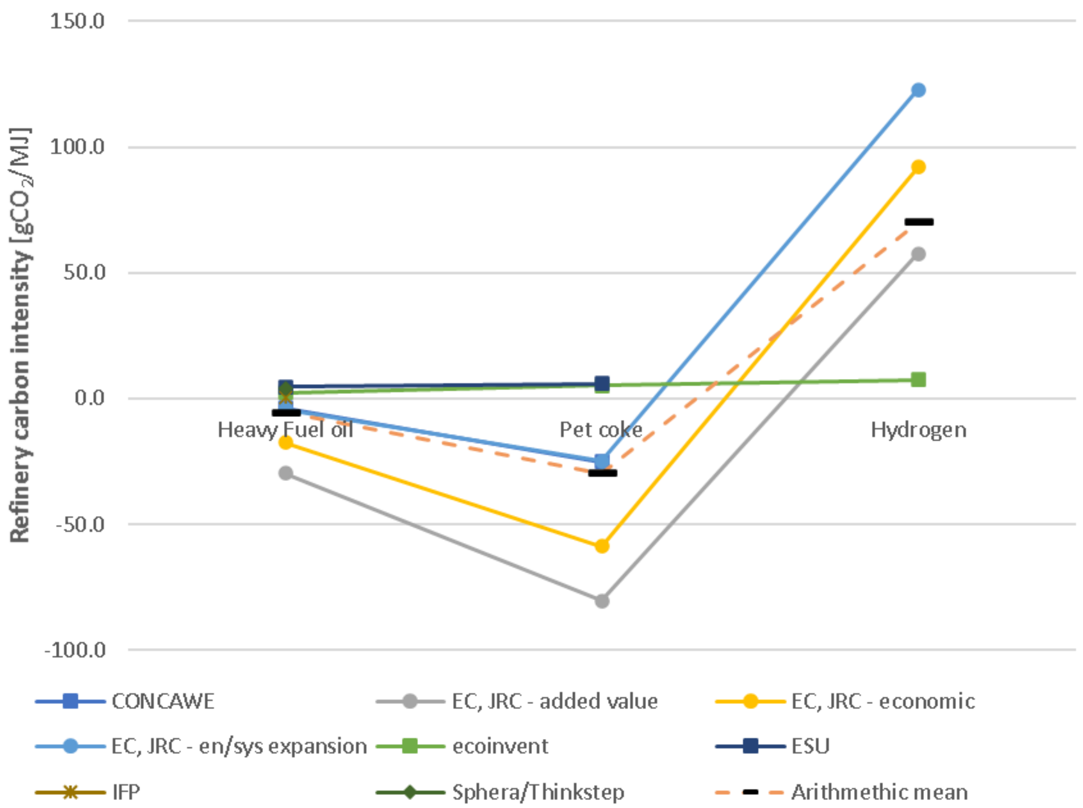


Figure 2: Variation of the reported carbon footprints for the three most-spread, non-primary products



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The horizontal variation, i.e. the spread of carbon footprint values within a given source, is not consistent (Figure 1, Figure 2). There is not a consistent higher-lower pattern to the sources.

Negative footprints are reported by some of the sources for four products: heavy fuel oil, bitumen, petroleum coke and sulphur. This is a consequence of heavier products needing less refining, resulting in lower energy demand and reduced refinery emissions overall, and the marginal method accounting for the emissions avoided by not converting these products further (e.g. to the main transport fuels). (Moretti et al., 2017) This implies that while the overall burden of refinery operation remains the same, the lighter and more refined fractions are assigned the full additional (i.e. marginal) burden from process steps intended to increase the yield of these product , e.g. hydrocracking.

4.2 Multiple views of the European Commission

Four organs of the European Commission have sponsored the estimation of refined product refining footprints: DGs Climate, Energy and Environment, and the Commission's Joint Research Centre. CONCAWE can also be considered an organ of the Commission in this context, because its footprint model is the reference for EU legislation (Moretti et al., 2017, p 372). Two of these sources - DG Climate and DG Environment – have not published disaggregated results, with the refining-only portions showed separately, for their carbon footprints, but as noted above, DG Climate reports that its refining footprints are in line with CONCAWE model.

With respect to the major products of diesel, petrol and jet fuel, the Commission's footprints have factors of 1.3-1.4. For peripheral products heavy fuel oil, petroleum coke and hydrogen, the spread factors are much larger: 8.1, 3.2 and 2.1 respectively.

4.3 Refinery modelling as the main source of variation

The main source of carbon footprint variation appears to be the approach taken to refinery modelling. All datasets are purported to represent the same system: European (EU + EFTA) refineries. Instead, there are different ways for assigning the overall burden arising from the petroleum refinery operation to the individual product outputs. The differences in partitioning and allocation – both are normative modelling aspects – are widely recognised as contributing to the variation. There is some variation among the datasets as data sources and methods of data collection: this appears to have some impact on overall variation. The varied age of the datasets does not seem to significantly affect overall variation.

4.3.1 Partitioning

Partitioning methods accounts for some of the overall variation in footprints. Within the main products: marginal partitioning generally gives diesel (and distillates) a higher footprint than unit process average-based partitioning; and the inverse for petrol (**Error! Reference source not found.**)[5]. This makes sense, given that European refineries are already configured to maximise diesel output (Europe imports diesel and exports petrol (FuelsEurope, 2019, p 11).

[5] The black-box method seems attuned to the attributional method. Rather than breaking the refinery into multiple unit processes (boxes), it treats the entire refinery as a single box, but the basic approach is the same, and surely it is not marginal.

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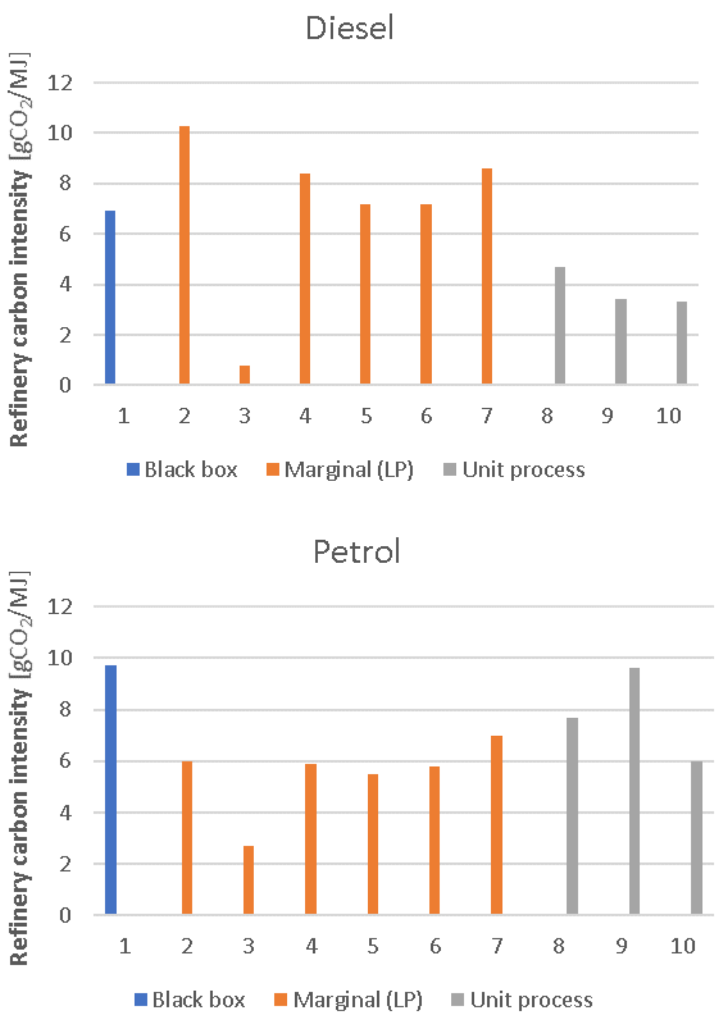
(Sphera et al., 2020, p 11) contend that the diesel-petrol difference is due to differences in how the methods treat hydrogen from the refinery's catalytic reformer. The marginal methods put more of the burden on hydrogen, while unit-process methods put more of the burden on the reformate (which goes mainly to petrol). Indeed, (National Energy Technology Laboratory & US Dept of Energy, 2008, p 63) proposes a separate partitioning of hydrogen within the refinery, but this approach does not seem to have been adopted by any of the European dataset producers.

Figure 3: Comparison of diesel/petrol footprints by partitioning method



For peripheral products, the variation of unit-process versus marginal is more significant. Spreads are much larger (Figure 1), and marginal partitioning generates negative footprints for some products. As (Moretti et al., 2017, p 380) points out, negative footprints reflect the fact that refineries would reduce emissions if they sold more of these products instead of increasing emissions to convert them into lighter products under a given set of demand and capacity constraints. Seen in an economic light, this is reasonable. These are unavoidable co-products, even considered residues[6]. Upgrading them into main products causes

[6] One heavy grade of fuel oil is even called 'resid'.

additional emissions and reduces yields at the refinery. At the same time, the resulting negative footprints can be problematic, in that they:

- Can confuse non-experts: it might be seen that if more, say, heavy fuel oil or petroleum coke were used, the environment will be cleaner. 'Use more HFO, save the planet.' This is not the case. The reality is that while more supplying more HFO or coke as final products (rather than upgrading them to other fuels) reduces overall emissions at the refinery, it also passes emissions down the supply chain to the user. That is, any perceived 'benefits' in refining can be expected to be eliminated when the full life cycles (i.e. cradle to grave) of the heavy products are considered. The trade-offs here are worth further investigation.
- Add greatly to footprint variance – of course the same could be said for the other attributional method – the point is that variance is wide.

Differences in partitioning have been addressed by several authors. IFP has made the case for the marginal method in numerous papers (Babusiaux, 2003) (Babusiaux & Pierru, 2007) (Tehrani Nejad M, 2007) (Pierru, 2007a) (Pierru, 2007b) (Prieur & Tilagone, 2007). IFP also was a driving force in CONCAWE's adoption of the method (CONCAWE, 2017)[7], which according to (Moretti et al., 2017) is now the reference in EU legislation. By contrast, a recent study sponsored by the European Commission (DG Climate et al., 2020, p 274) declined to use the CONCAWE model because of its 'incremental' partitioning method based on marginal analysis; a disaggregated unit process model with step-by-step co-product allocation was used instead.

The black box method of no partitioning was adopted by a relatively old study (PlasticsEurope & Boustead, 2005) that reported only one product footprint, for naphtha. Only one current study (ESU-Services et al., 2018) adopts similar approach, in which total resource use and emissions from refinery operation are assigned to the individual products predominantly in a 'top-down' fashion. In this case, though, the authors apply various factors to reflect differences in routes and degree of refining needed to obtain the final products. Its footprints are higher than many of the datasets, but this is probably due not to partitioning, but to sources of data (see 4.3.3). The black box or top-down approach differs to the unit-process-partitioned models in that it lumps all conversion processes together from refinery-input to refinery-output, whereas the unit-process datasets are generated by modelling each major process in the refinery separately. The attributional approaches (for assigning the burdens of a specific process step or the entire refinery to the respective product outputs) are nonetheless similar.

Two artefacts associated with partitioning merit further research. One is the relationship of unit-process fuel types and product footprints. For instance, fluid-cat-crackers are fired mainly by the coke that accumulates on its catalyst. This coke is burned to regenerate the catalyst and to fuel the process. This coke is similar to coal, i.e. very carbon intense, so cat cracker outputs bear a higher footprint than those same products coming from other refinery units. It would be interesting to see a comparison of footprints calculated using unit-specific fuels versus a common fuel mix across the entire refinery.

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[7] This is acknowledged in the paper and confirmed in personal communication with A. Tehrani Nejad.

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The other artefact is the definition of residues (or unintended products) in unit-process partitioning. (DG Climate et al., 2020, p 273) defines: residues as streams that are bottoms in two consecutive unit-processes; distillates are always considered as products. However, 1) the same study does not classify bitumen as a residue, and 2) LPG, which is always a distillate, might be considered a residue, in that most refiners try to minimise its production.

4.3.2 Allocation

Among the main refined petroleum products, allocation based on mass or energy-content yield almost identical results, because their energy densities are very similar. For peripheral products this is not the case, and several products are not used for energy: namely bitumen, lubes/wax, sulphur and some petroleum coke. Only one source shows this difference (Eurobitume, 2012) (Eurobitume, 2019). The spread of an economic allocation basis to an allocation based on physical causality (heating energy requirements[8]) for bitumen is a factor of 2. This is less than the spread overall for bitumen (Table 3).

(ESU-Services et al., 2018, Table 13.2) uses energy as its allocation key, but not the 'per-MJ-of-product' approach applied in other energy-allocated datasets. Instead it applies 'energy factors' derived in 1996[9] that are reported as a percentage of the refinery-average-energy required to process a given product.

4.3.3 Sources of data and methods of collection

There are two approaches to this are applied:

- Engineering models of a refinery (i.e. a collection of unit processes), which are used in all but two of the datasets.
- Top-down estimation of resource use and emissions from literature and industry statistics, as applied by (PlasticsEurope & Boustead, 2005) and (ESU-Services et al., 2018).

Of the 11 product footprints reported by (ESU-Services et al., 2018), five are the highest of all datasets (Table 2). The reasons for this are not obvious, but it is likely due to this different approach to sourcing and collecting data. This is unlikely to be a significant variable in those that use a similar approach, especially in five of the six datasets from the European Commission and the CONCAWE dataset, which presumably are based on a common set of raw data. The one European Commission dataset not in common, that from DG Climate, reports that its findings are anyway in line with CONCAWE's (Table 2).

4.3.4 Age of the datasets

The age of the datasets does not appear to be a significant variable. The two significantly older datasets – Plastics Europe and Statoil – report footprints that fall in the range of the more-modern datasets. This is the case, even though (CONCAWE, 2017, p 12) notes that since the early 2000s there have been significant changes in European refineries, including their crude slates, product demands, configurations and capacities.

[8] That is, the allocation is based on the relative amount of heat (energy) required to make each product.
[9] From a paper cited as: Jess A. (1996) Der Energieverbrauch zur Herstellung von Mineralölprodukten, *In: Erdöl-Erdgas-Kohle*, **112**(5), pp. 201 - 205

4.4 Product category boundaries

Two sets of paired products seem to have ambiguous boundaries. Diesel and heating oil are paired products in that they are chemically similar (and sometimes even identical). Petrol and naphtha are paired in that they have similar properties: whereas petrol is more aromatic, petrochemical naphtha is more aliphatic, but both have similar boiling ranges. For the four sources that report footprints for both pairs (Table 2), the values petrol and naphtha footprints always differ from each other, suggesting that they are indeed different products, either obtained over different process routes or not assigned identical allocation factors.

However, for diesel and heating oil, two sources report the same footprint for them while the other two report different values. This suggests a possible difference of opinion, by source, as to the definition of diesel and heating oil. It also suggests that other sources, which report only diesel and not heating oil, assume the two to be the same thing. At the same time, it is also possible that similar (or identical) products are coming are coming from different unit processes, and therefore considered as separate products – although in the real-world market they are not separate.

5 Conclusion

This paper finds that the reported footprints for European refining of the main refined products – diesel, petrol and jet fuel – vary by a factor of three. For minor and peripheral products, the variation is even greater, reaching a maximum of almost 20. There is also horizontal variation within each dataset; this does not follow a consistent pattern. Five different organs of the European Commission have estimated refining footprints: for main products these are relatively harmonic; for minor products much less so.

The variation is due not to a variety of physical or operational characteristics, rather it is due to a variety of modelling methods. A clear cause of variation between datasets is the use of different partitioning methods. This also contributes to horizontal variation. Differing allocation keys make a difference in peripheral products, but not in the main products. Differing approaches to data-sourcing and -collection also contribute to the variation.

This variety of footprints is important not only to researchers but to policymakers and actors up and down the petroleum supply chain, because petroleum footprints are significant in general, and they are increasingly used in regulation.

6 Author information, contributions, ethics

Eric Johnson is the Managing Director of Atlantic Consulting (Gattikon, Switzerland). He is Editor-in-Chief Emeritus of Environmental Impact Assessment Review.

Carl Vadenbo works as a project manager for the ecoinvent association, a not-for-profit organisation and the publisher of the ecoinvent LCI database, based in Zürich, Switzerland.

Both authors made considerable contributions to the design, analysis and discussion of the study presented in the present paper. Both authors have read and agreed to the published version of the manuscript.

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