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# Allocation of $CO_2$ emissions in petroleum refineries to petroleum joint products: A linear programming model for practical application

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**Abstract**

The allocation of $CO_2$ emissions associated with petroleum refineries to petroleum joint products is a necessary step in Well-to-Tank analysis in order to evaluate the environmental impacts of individual automotive fuels. Oil refining is essentially a joint production system and due to the complex nature of the process involved, it is very difficult to establish any noncontroversial allocation pattern for oil products. Under certain conditions, however, refinery linear programming models can provide a non-arbitrary additive allocation schema based on the marginal contribution of each oil product to the total $CO_2$ emissions. But in general, these conditions are not satisfied.

In this paper, by extending the LP approach to the optimal Simplex tableau, we propose an original two-stage methodology based on the marginal contribution of oil products and the production elasticity of unit processes to provide an additive $CO_2$ allocation scheme. We show that this procedure emerges from the equilibrium behavior of the refinery and is consistent with microeconomic theory. A numerical example is provided.


*JEL classification:* Q4; Q51; C61

*Keywords:* Joint production; $CO_2$ emissions allocation; Refinery; Linear programming; Simplex method

## 1. Introduction

The question about industrial energy that this paper addresses is the allocation of the refineries' $CO_2$ emissions to petroleum joint products. This allocation procedure constitutes a necessary step

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in evaluating the environmental impacts of automotive fuels in Well-to-Tank (WTT) studies. In fact, WTT is the first part of Well-to-Wheel (WTW) studies and consists in assessing the energy consumption and the resultant $CO_2$ emissions along fuel chains from the extraction of feedstock until the delivery of fuels to the vehicle tanks.[1] Since the WTT differences among automotive fuels are due exclusively to the refinery component, especial care should be taken on the allocation principle used to assess the contribution of oil products to the refinery energy use and $CO_2$ emissions. Oil refining is a joint production system and due to the complex nature of the process involved and the vast number of joint product outputs that are strongly correlated, it is very difficult to establish any noncontroversial allocation scheme for oil products.

In practice, allocation rules used so far for the petroleum-based fuel are traditionally based on two fundamental approaches: physical measures (mass, volume, energy or exergy[2] contents, molecular mass or other relevant parameters) or market value (gross sale value) or expected economic gain of individual oil products from a given refinery. Both of these approaches inevitably involve the use of arbitrary allocation rules.

Furoholt (1995) and Wang et al. (2004) point out that these allocation rules should be applied at the sub-process level within a refinery and not at the aggregate process level (i.e., the refinery level). This would consist in partitioning the refinery into different process units and then allocating the energy consumption and the resultant emissions from each process unit to the products from these units according to mass, energy content or market value of final and intermediate petroleum products. They show that, contrary to the aggregate process level, tracking energy use and emissions by individual refining process helps reveal some additional energy and emissions associated with certain refinery products that are otherwise overlooked with the refinery-level allocation.

Although the "process-level-based method captures process-dependent characteristics of fuel production within a petroleum refinery" (Wang et al., 2004) it is still open to discussion on two points. First, despite the important effort of tracking the energy use and emissions by individual refining process, this approach still suffers from using arbitrary rules at its final step. In this regard, Azapagic and Clift (1999a,b) show how these arbitrary measures break down in joint production industrial systems when they do not reflect the underlying physical causality and lead to flawed results. For instance, in a Life Cycle Assessment study for the Statfjord production platform for production of regular gasoline, Furoholt (1995) reports that, based on the volume criterion, only 0.5% of the total energy use and the resultant emissions is allocated to gasoline, whereas it is 81% based on the energy criterion and 57% based on detailed partitioning.

Second, the sub-process allocation approach provides an incomplete picture of the whole system as it ignores the complex interactions, interdependencies and synergies which exist among the refinery oil products and process units. As a consequence, this approach systematically assigns more energy use and $CO_2$ emissions to the oil products that utilize more process units. An illustrative example of this issue is gasoline and diesel which constitute the two main automotive oil products in WTT and WTW analysis. Most of the existing WTT studies overestimate the environmental burdens (energy use and $CO_2$ emissions) of gasoline due to the higher number of gasoline processing units in European refineries (an exception is the WTT report of CONCAWE

[1] WTW and WTT studies are categorised in retrospective and prospective approaches. Prospective studies are based on marginal data and consider the effects of different decisions. On the other hand, retrospective studies are based on average data and study the environmental accounting issues. Throughout this paper, we only focus on the retrospective approach.

[2] The exergy content of a system indicates its distance from the thermodynamic equilibrium. The higher the exergy content, the farther from the thermodynamic equilibrium (definition from, http://www.holon.se/folke).