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# A Quasi-Input-Output model to improve the estimation of emission factors for purchased electricity from interconnected grids

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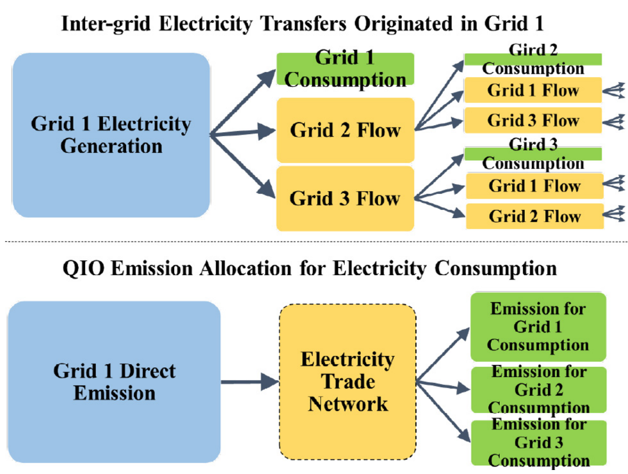
## HIGHLIGHTS

- A new method is proposed to measure emission factors of electricity consumption.
- Comparisons with previous methods show significant improvement.
- A case study is conducted to demonstrate the method.
- Our method can be applied to measure other impacts of electricity consumption.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Estimating the embodied emissions in electricity has been a challenge due to the interconnectedness of electrical grids. Previous studies use a variety of methods that are often inaccurate or difficult to implement, lacking a standardized tool. We propose a method adapted from the economic input-output theory, which we term as "Quasi-Input-Output (QIO)" model, to evaluate embodied emissions in purchased electricity. The method takes into account the difference between the natures of trade in electricity and in goods and services, able to capture the effects of both direct and higher-order electricity transfers in the network. We use the Eurasian Continent grid network as a case, identifying regions where inter-grid electricity transfers, both direct and high-order, have sizable impacts on estimated emission factors of purchased electricity. Overall, while ignoring electricity trade can result in errors in embodied emissions estimation, directly adjusting for electricity trade (neglecting higher-order trade) tends to generate inaccuracies in the opposite direction. Our model can be potentially applied as a standard tool for the

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accounting of embodied emissions in purchased electricity in inter-grid electricity trade systems. It also provides a foundation for further applications of input-output theory in the analysis of demand-side drivers for environmental impacts of interconnected grids.



## 1. Introduction

Electricity generation is a major source of environmental impacts such as emissions of greenhouse gasses (GHGs) and air pollutants [1,2]. For example, it contributes to approximately 42% of global $CO_2$ emissions [3]. As such, various environmental reporting outlets require the information on the emissions embodied in purchased electricity. For example, the California Environmental Quality Act (CEQA) requires eligible organizations to report not only their direct GHG emissions from on-site but also GHG emissions from purchased electricity [4]. Likewise, both the Carbon Disclosure Project (CDP) and the Global Reporting Initiative (GRI) recognize emissions from purchased electricity as a separate category [5,6]. Methods for accounting emissions from purchased electricity have also been recognized as a topic for scientific inquiries [7,8].

From the practitioner's point of view, however, such issues boil down to emission factors, which are the amount of emissions embodied in the unitary electricity consumption. For example, the Greenhouse Gas Protocol [9], a widely used GHG accounting guideline used by many GHG emission reporting outlets, explicitly includes an organization's indirect GHG emissions due to consumption of purchased electricity (called scope 2 emissions), which are generally calculated using emission factors. The accuracy of GHG emission accounting, therefore, hinges in part on our knowledge about emission factors of purchased electricity [8].

A challenge in accounting emissions from electricity is the complex electricity trade. Electricity trade among power grids is sizable and increasing, giving rise to important spatial uncertainties in the estimation of emissions embodied purchased electricity from interconnected grids. According to International Energy Agency (IEA) statistics [10], in 2013, the OECD countries imported and exported 440 million MWh and 410 million MWh of electricity respectively, each amounting to approximately 4% of the total OECD global electricity generation. From 2010 to 2013, the OECD electricity imports and exports grew roughly 6% annually, while in the same period, the OECD electricity production remained almost the same. In the United States, there are also substantial interregional electricity transfers. For some subregions in the eGRID database [11] of the United States Environmental Protection Agency (USEPA), the ratio of power originating from outside the consuming subregions to total consumptions exceeds 25%. Electricity trade poses challenges to emissions accounting for electricity consumption because the consumed electricity in a power grid can originate from other grids with substantially different fuel choices for electricity generation. This energy arrives at the consuming grid through a complex network which obscures the energy's source. For instance, a grid may purchase electricity from another grid, and this purchased electricity may contain the electricity that the second grid purchased from a third grid, etc.

Existing studies use three categories of methods to calculate embodied emissions in electricity. The first category estimates emissions embodied in electricity consumption simply with emission factors defined as the ratio of total directly released emissions to the electricity generated in a region, ignoring the effect of electricity trade. For example, the eGRID database of the US-EPA divides the country into 26 subregions and recommends using emission profiles of each subregion's local power plants to attribute emissions to electricity consumption in the subregions [11,12]. Emission accounting for electricity use in the Nordic countries also neglects the effects of interregional exchanges [13–15].

The rising importance of electricity transfers among regions has inspired the second category of methods, which adjusts for only direct imports and exports (i.e., adding emissions embodied in electricity imports and deducting those embodied in exports in accounting for consumer responsibility) [7,16–19]. We term this method as the *direct transfer method*. Here the emissions embodied in electricity trade are estimated using the ratio of the exporting grid's directly released emissions to its electricity generation. Therefore, such adjustments cannot lead to accurate results if interregional transmissions are commonplace across the entire network (i.e., regions import electricity from others which in turn have imported much of their electricity).

The third category of inter-grid emissions estimation consists of studies that account for the network-wide impacts of purchased electricity. Those studies aim to capture the embodied emission flows within electricity supply chains of the inter-grid network. There are a variety of approximation techniques which suffer different methodological issues, as we review below.

Previously, we estimated emission factors of purchased electricity based on a modified Input-Output (IO) approach [20]. The model treats emissions as an external multiplier, which is usually done in traditional environmentally extended input-output (EEIO) studies. However, in order to map electricity generation in the electricity trade network to product outputs in the IO model, the intermediate exchange matrix must be composed of net inter-grid power flows. Since the electricity transfers between two grids are often bi-directional, the previous method is not viable and causes errors in embodied emission analysis.

Zhu et al. [21] calculated virtual water transfers due to electricity transmission among six interconnected power grids in China with the physical network structure (i.e., which power grid is connected to which, and the total amount of electricity each power grid sends out and receives). Their method, in theory, can be used for inter-grid emission estimation. However, in very complex networks, this method cannot derive correct results, because it ignores the differences in the amount of electricity that each grid sends to multiple other grids. The most accurate method in the literature (to our knowledge) is an iterative algorithm [22], allocating electricity generation and the associated emissions to different regions following a large number of transmission paths. However, this method is only approximate in its construction since the iteration must stop in finite steps. (We will discuss the latter two methods and compare them with our model in Sections 4.2 and 4.3.)

This paper aims to provide a standard framework to evaluate emissions embodied in electricity in the interconnected grid network, where electricity trade is intensive. We focus on grid-average emissions or emission factors over a certain period.

We propose a method by applying the framework of Input-Output (IO) theory to the analysis of interconnected grid network. The IO theory has been widely used as a tool to quantify interregional emission transfers [23–28]. We modify the IO framework considering the specific nature of electricity trade, and thus term our model the "Quasi-Input-Output (QIO)" model. (Differences between the IO and the QIO model is discussed in Section 4.1.)