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Assessment of nuclear energy embodied in international trade following a world multi-regional input–output approach

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ABSTRACT

Nuclear power can contribute to cover the increasing demand of energy while keeping the carbon emissions within the desired limits. Many countries are reluctant to implement nuclear technologies in their territories, but might still use them through imports of products that embody nuclear energy in their life cycle. This work quantifies the difference between the production-based (territorial) and consumption-based (global) nuclear energy use in the main 40 economies of the world (85% of the world's GDP) through the application of a multi-regional environmentally extended input–output model. The mismatch between the direct (territorial) and total (global) use of nuclear energy varies from −237% to 44% in the top economies. From a consumption-based viewpoint, 10 out of the 40 countries reduced the per-capita use of nuclear energy in the period 1995–2009, and 7 when following a production-based approach. The per-capita nuclear energy use could differ in up to 26.2 GJ/inhabitant·year, depending on whether the assessment is consumption or production based. It was also found that around 3.5% of the world's nuclear energy production is trade-embodied and that this amount is growing along with the global production of nuclear energy. Our findings might help to develop more effective environmental regulations worldwide.

1. Introduction

Climate change has attracted an increasing attention due to the continuous rise in energy demand [1]. Presently, renewable and nuclear energy sources are the most promising alternatives to meet the growing energy demand and keep simultaneously GHG (greenhouse gas) emissions below the desired limits. Unfortunately, in the current energy scenario and considering the capacity already installed, these energy sources are still unable to fully replace fossil fuels. In addition, they show major shortcomings that remain unsolved and have prevented their full deployment. Renewable energy technologies are still expensive [2–5], and their energy yield is highly constrained by on-site resources availability. On the other hand, nuclear energy has raised major concerns regarding its impact on current and future generations. Mining, processing and enrichment of uranium cause substantial damage to ecosystems and waterways [6]. Moreover, nuclear power plants require large amounts of cooling water that may cause thermal pollution when discharged into the local ecosystem [7]. Life cycle assessment studies on nuclear energy have found that waste storage and disposal represent the most contentious issues for nuclear power [8], mainly because no country has a final repository for high-level waste [9].

Overall, there are two main serious externalities related to nuclear energy. The first is the risk of a nuclear accident with very high environmental impact (e.g. Three Mile Island, Chernobyl and Fukushima). The second is the generation of radioactive residues (whose final disposal poses serious environmental and safety issues in the long term). Some studies have also found that the life cycle emissions per unit of nuclear energy (including mining, milling and transporting of uranium) are similar to those associated with natural gas power plants [10], which questions the environmental benefits of a move towards nuclear energy.

Recent advances in nuclear industry safety have reduced the probability of experiencing future incidents. However, there are still some risks that cannot be entirely eliminated (e.g. natural disasters). Regarding nuclear residues, safe ultra-long-term storage of nuclear waste is still an unsolved problem which may cause serious

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future externalities difficult to quantify or predict (including human health negative effects, biodiversity loss, land degradation and diverse social costs, to name some). For these and other reasons, nuclear energy has led to social reactions evidencing that these activities are not well received in their neighboring areas.

In today's globalized markets, industrial sectors around the world make use of a plethora of energy sources to manufacture their products, including nuclear power. In this context, countries without nuclear plants in their territory might make indirect use of nuclear energy through the consumption of goods and services imported from countries that produce it. Thereby, indirect nuclear energy consumers benefit from it (via trade) without undergoing the associated negative effects.

It is clear that countries without nuclear facilities but which consume goods manufactured with nuclear energy externalize the corresponding negative effects to the manufacturing regions where nuclear facilities operate. A fair assessment of nuclear energy use should therefore consider both: (i) the amount of nuclear energy directly consumed within the geographic limits of a given nation; and (ii) the amount of nuclear energy embodied in the goods imported by the country via international trade. Thereby, nations willing to lower the environmental loads derived from nuclear energy should reduce the nuclear power share in their energy mix, but at the same time consume less products manufactured with nuclear energy. Consumption-based environmental assessments are therefore more appropriate than production-based (territorial) ones, as they capture direct as well as indirect effects.

Data of territorial nuclear energy production can be retrieved from specialized databases (e.g. the International Energy Agency [11]). In contrast, consumption-based data require information on the international channels through which goods and services are traded [12]. Macroeconomic IO (input–output) models [13] offer an appealing framework to gather the necessary information to perform such an analysis. They track goods and services internationally traded, thereby providing an exhaustive description of macroeconomic transactions between productive sectors and final consumers. Macroeconomic models have found many applications in different areas during the last 40 years [14], including the study of energy related topics (e.g. electricity). Han et al. [15] used an IO model to analyze the power sector in the Korean economy, where nuclear power plays a major role. Later, Yoo and Yoo [16] studied the role of nuclear power in the economic development of Korea. These IO studies focused on the economic impact of power generation and disregarded the associated environmental effects.

Environmentally extended IO models assess economic and environmental issues simultaneously, thereby establishing a solid link between economic output and environmental loads [17]. Through the application of EEIO (environmentally extended input–output) models, the economic output of a sector is translated into tangible environmental loads. EEIO models have been extensively used in environmental assessments due to their flexibility, accuracy and transparency [18]. In the context of energy related topics, EEIO models have been used to quantify energy-related GHG emissions [19], and to study the direct and indirect energy consumption in households [20–23] as well as in specific sectors [24–27]. EEIO models have also been widely used in the assessment of the amount of energy and GHG emissions embodied in trade [28–33]. Other works have employed EEIO models to assess toxic emissions to air [34–36], and quantify the water footprint of several economies and sectors [37–42]. In the energy field, however, very few studies have used IO models to assess energy sources others than fossil fuels (and to the best of our knowledge, no study of this type has focused on nuclear energy). Moreover, studies published so far restricted the analysis to one single economy and one specific year [43]. Some approaches extended the analysis to the multi-regional case [44], but did not cover the evolution of the economies over time. Furthermore, no single study has compared the production-based vs. the consumption-based amount of nuclear energy in each country and the role played by international trade on its use.

This work assesses the extent to which the world's main economies (i.e. those covering 85% of the world's GDP) consume nuclear energy either directly or indirectly (i.e., considering both, their national energy grids and the grids of the countries from where they import goods/services), paying special attention to the period 1995–2009. The analysis is carried out using EEIO tables retrieved from the WIOD database (world input–output database) [45].

The remainder of this paper is organized as follows. Section 2 describes multi-regional EEIO models and how to calculate the consumption-based/production-based nuclear energy use and the amount of nuclear energy embodied in international trade. Section 3 presents the main findings of this research work, while the conclusions of the study are drawn in section 4.

2. Materials and methods

This section starts by introducing the general structure of IO models in a single economy and then extends them to deal with multi-regional economies. The following section describes how to assess the total nuclear energy use according to the production-based and consumption-based approaches.

2.1. Input output analysis

IO models are well established in the literature. The interested reader is referred to the text book by Miller and Blair [14] for a detailed description of EEIO models, including the assumptions underlying them. The analysis described herein is based on the WIOD database, which considers 35 sectors and 40 countries (during the period 1995–2009.), plus an additional region representing the rest of the world [45]. From the 40 countries studied, 27 of them belong to the European Union and 13 to other major countries, which all together represent more than 85% of the world's gross domestic product.

2.1.1. Single region IO models

In an IO model of a given economy, macro-economic transactions occur between selling economic sectors i and consuming sectors j, resulting into economic flows z_{ij} of goods/services measured in monetary terms (intermediate sales), in a given time period (e.g. annually). Additionally, there are other exogenous consumers (e.g. households, government and international trade) demanding products from each sector (i.e., final demand). On this basis, in a given economy with n sectors, the total economic output of a sector i is denoted by x_i, while y_i represents the final demand from the final consumers of sector i. as shown in Eq. (1) expresses the total output of sector i as a function of the final demand and the intermediate sales.

$$x_i = z_{i1} + \ldots + z_{ij} + \ldots + z_{in} + y_i = \sum_{j=1}^{n} z_{ij} + y_i \ \forall i \quad (1)$$

Note that the number of equations of this type equals the number of sectors of the economy (n), which leads to n economic outputs, n final demands, and n^2 intermediate flows. For convenience, a matrix notation is used, in which capital letters denote matrices and vectors, while lowercase letters refer to their elements (see Eq. (2)).