Energy 82 (2015) 578–588

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Solar energy embodied in international trade of goods and services: A multi-regional input–output approach

D. Cortés-Borda [a], G. Guillén-Gosálbez [a, b, *], L. Jiménez [a]

[a] Departament d'Enginyeria Química, Universitat Rovira i Virgili, Av. Països Catalans 26, 43007 Tarragona, Spain
[b] Centre for Process Integration, School of Chemical Engineering and Analytical Science, The University of Manchester, Manchester M13 9PL, UK

ARTICLE INFO

Article history:
Received 28 March 2014
Received in revised form
20 January 2015
Accepted 21 January 2015
Available online 4 March 2015

Keywords:
Input–output analysis
Solar energy
Trade embodied energy
Production-based
Consumption-based

ABSTRACT

In a globalized market, part of the goods/services consumed in a country might be produced abroad using diverse energy sources. To properly assess the extent to which a country is moving towards more sustainable energy sources, it is imperative to consider both, the amount of renewable energy produced within its boundaries along with that embodied in the imported goods/services. This work quantifies the amount of solar energy embodied in trade using environmentally extended input–output models. Numerical results reveal that some countries are net importers of solar energy (the amount of solar energy consumed anywhere in the world for producing the goods and services they require is greater than the amount of solar energy they generate locally), while others are net exporters (the opposite situation occurs). Additionally, it was found that the production of solar energy in the top economies has increased in the last two decades. Our analysis aims to facilitate the design of more effective environmental policies for promoting the use of solar energy worldwide.

1. Introduction

High levels of greenhouse gas (GHG) emissions have prompted nations to implement strong measures to mitigate global warming. The European Union (EU), through the Kyoto protocol, agreed a common GHG reduction of 8% during the period 2008–2012 with respect to 1990. In this context, the use of renewable energy sources plays a key role in the accomplishment of the GHG-targets sought. Specifically, the European commission established the objective of covering with renewable energies (mainly biomass, hydropower, wind energy and solar energy) 12% of the EU's gross inland energy consumption by 2010 [1,2]; and established as well target shares of renewable energy sources in the individual member states in 2010 [3]. Energy consumption can be benefited as well with other renewable energy sources (e.g. energy storage options [4,5]) to shift the loadings to reduce GHG emissions.

These stringent regulations, however, might be ineffective if nations avoid them by displacing their manufacturing tasks to regions with weaker environmental legislation [6]. To properly assess the extent to which a region is moving towards a cleaner energy system, it is necessary to consider simultaneously the energy generated within its geographical limits along with the energy employed in the production of the goods it consumes (note that part of these goods might be produced internally and another part externally). Hence, nations willing to reduce their GHG emissions should increase the share of renewable energy sources in their energy systems, but at the same time consume products manufactured using mainly renewable resources.

The idea of assessing the impact over all the stages of a product is not new, but it is only now that we have the proper data available to conduct this type of analysis in an international scenario. In fact, several policy instruments have been introduced recently to promote the consumption of environmentally efficient products among consumers. Particularly, there is a growing interest on Eco-labeled products [7]. Eco-labels quantify the environmental performance across the whole product supply chain in terms of a wide variety of impacts taking place in different stages of the life cycle of the product/service under study. Hence, the use of eco-labels might lead to global environmental savings (in addition to other local benefits), which are ultimately achieved by guiding customers towards products/services with less environmental impact. Energy consumption is a major source of impact in any process. Hence, it is

* Corresponding author. Departament d'Enginyeria Química, Universitat Rovira i Virgili, Av. Països Catalans 26, 43007 Tarragona, Spain.
E-mail address: gonzalo.guillen@urv.cat (G. Guillén-Gosálbez).

http://dx.doi.org/10.1016/j.energy.2015.01.067
0360-5442/

of key importance to assess the energy portfolio used in the production of goods and services so as to promote more sustainable products involving less impact over their entire life cycle. This task is challenging because in today's globalized markets goods and services are exchanged through complex international channels that are not fully characterized.

This work makes use of macroeconomic models based on interregional world input–output tables retrieved from the WIOD database [8] to assess the global use of solar energy in the wealthiest economics of the world. The production-based energy use (solar energy use within the limits of the country, an information published by the International Energy Agency [9]) is compared with the consumption-based one (amount of solar energy consumed anywhere in the world to produce the goods and services demanded by a country [10]) in order to identify countries with significant differences between both.

Macroeconomic input–output (IO) models [11] offer an appealing framework to conduct consumption-based studies, as they contain information on the goods and services traded internationally. More precisely, IO models provide an exhaustive description of the economic transactions between final consumers and productive sectors in an international scenario. These models can be extended to capture environmental issues, thereby providing a solid link between the total economic output of each productive sector and its corresponding energy consumption and pollution intensity [12]. The resulting environmentally extended input–output (EEIO) models, which include macro-economic and environmental information, allow translating the economic output of a sector into tangible environmental loads (e.g. GHG emissions, energy expenditure, and/or consumption of natural resources).

EEIO models have been extensively used in environmental assessments due to their flexibility, accuracy and transparency [13]. Particularly, in the context of energy related topics, EEIO models have been used to conduct a plethora of studies, including the assessment of energy-related CO_2 emissions [14–18]; the estimation of direct and indirect energy consumption in households [19–25] as well as in specific sectors [26–29]; the estimation of the energy embodied in international trade [30–36]; and the estimation of the effects of adopting environmental policies [37,38]. Macro-economic EEIO models, however, have never been used so far to quantify and compare the consumption-based and production-based solar energy use of the main economies, in a multi-regional economy.

Our study assesses the amount of solar energy (both thermal and photovoltaic) embodied in international trade, paying special attention to the top 10 wealthiest economies in the world during period 1995–2009. These economies cover most of the solar energy produced worldwide (between 57% and 79% of the world's solar energy consumed in such time period). The comparison between the solar energy assessed from the consumption and production perspectives sheds light on the extent to which nations are effectively increasing their quota of solar energy, either locally (within their limits) or globally (considering the total energy use over the entire life cycle of the products they consume). Our analysis makes use of EEIO models that are constructed from information retrieved from the WIOD database, which considers 35 industrial sectors and 40 countries (representing 85% of the world's gross domestic product) and an additional "region" representing the rest of the world. Particularly, the following questions are addressed in this paper:

- To what extent is solar energy being used by the economic sectors of the top economies of the world?
- To what extent is solar energy being used to produce the goods and services consumed by these top economies?
- Which is the evolution of these two variables over time?
- Are the top countries net importers (import more solar energy via trade than the amount consumed internally) or net exporters (the opposite situation) of solar energy?

The structure of this article is as follows. Section 2 presents an illustrative example that motivates this piece of research. Section 3 describes the multi-regional EEIO model used in this work, which allows quantifying the solar energy use following the two approaches. Section 4 describes the database used in the calculations and discusses the main findings obtained from the numerical analysis of the data. Finally, the conclusions drawn from the analysis are exposed in Section 5.

2. Illustrative example

To motivate the approach presented, let us introduce a hypothetical illustrative example with 3 countries (A, B, and C) and two productive sectors in each of them. Each country has its own production technologies and therefore shows a different overall environmental performance. It is considered that among the 3 hypothetical countries, B is the one with the best environmental performance and C the one with the worst (it is further assumed that countries with larger shares of solar energy show better environmental performance).

Table 1 summarizes the EEIO model associated with the global economy, which takes into account the international trade structure and its environmental extension (i.e., amount of energy embodied in every economic activity). The rows represent the sales of sectors of one country to sectors of any country (e.g. the first row are the sales of sector 1 of country A, to the sectors of all of the remaining countries), and the columns represent the purchases made by each country and sector. The total output of a sector is given by the sales to intermediate sectors of the same and other countries along with the final demand covered by the sector. As an example, sector 1 of country A (see the first row of Table 1), sells 23 and 32 M € to its own sectors (1 and 2, respectively), 1 and 4 M € to sectors 1 and 2 of country B, respectively, and similarly 5 and 9 M € to the sectors of C; in addition, it sells 16 M € to the final consumers of A, 3 M € to the final consumers of B, and nothing to the final consumers of C. Hence, the total sales of sector 1 of country A are 93 M €. Regarding the purchases, sector 1 of country A (see the first column of Table 1), purchases 23 and 10 M € from sectors 1 and 2 of A, respectively, 3 and 1 M € from B, and 2 M € from each sector of C. The final demand column includes the purchases made by customers. As an example, final consumers of country A purchase 16 and 19 M € from sectors 1 and 2 (respectively) of country A, 9 and 5 M€ from B, and 1 M€ from sector 2 of country C.

The solar energy used in each sector is given by the product of the corresponding output with the solar energy intensity, while the solar energy use of a country is the summation of the solar energy consumed in each of its sectors. Hence, the solar energy use in each country is $A = 35.02$ TJ; $B = 40.01$ TJ and $C = 30.06$ TJ. Note that this environmental assessment is based on the total output, so the solar energy thereby calculated is production-based.

Hence, from a production-based viewpoint, solar energy use changes very little from one country to another. However, despite the fact that the three countries consume similar amounts of solar energy, there is one country (i.e., nation C) that employs a significant share of its solar energy to cover the demand of other economies (to manufacture goods that are ultimately exported) rather than to meet its own demand.

The consumption-based assessment accounts for all the transactions taking place anywhere in the world to satisfy the demand of a given country. Table 2 displays the economic transactions that