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Identifying strategies for mitigating the global warming impact of the EU-25 economy using a multi-objective input–output approach

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HIGHLIGHTS

- We minimize climate change by performing small changes in the consumption habits.
- We propose a tool that combines multiobjective optimization and macroeconomic models.
- Identifying key sectors allows improving the environmental performance significantly with little impact to the economy.
- Significant reductions in global warming potential are attained by regulating sectors.
- Our tool aids policy makers in the design of effective sustainability policies.

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ABSTRACT

Global warming mitigation has recently become a priority worldwide. A large body of literature dealing with energy related problems has focused on reducing greenhouse gases emissions at an engineering scale. In contrast, the minimization of climate change at a wider macroeconomic level has so far received much less attention. We investigate here how to mitigate global warming by performing changes in an economy. To this end, we make use of a systematic tool that combines three methods: linear programming, environmentally extended input output models, and life cycle assessment principles. The problem of identifying key economic sectors that contribute significantly to global warming is posed in mathematical terms as a bi-criteria linear program that seeks to optimize simultaneously the total economic output and the total life cycle CO_2 emissions. We have applied this approach to the European Union economy, finding that significant reductions in global warming potential can be attained by regulating specific economic sectors. Our tool is intended to aid policy makers in the design of more effective public policies for achieving the environmental and economic targets sought.

1. Introduction

The CO_2 atmospheric concentration, which is increasing at a rate of around 2 ppmv every year (Budzianowski, 2013), has become a major environmental problem over the last decades (Raupach et al., 2007). This has led to severe dangers for Earth's climates and ecosystems such as global warming, sea level rise and ocean acidification. In 2009, most of the atmospheric CO_2 emissions were emitted from fossil fuel combustion in various energy related applications (IEA, 2010). Worldwide national governments have placed greenhouse gas emissions mitigation as a high priority and have started to implement stringent measures based on the reorganization of the way in which society develops (work, transport, leisure, city planning, housing, electricity production, etc.) (Carvalho, 2012). A large body of literature has studied different technological alternatives to mitigate global warming by adopting an engineering approach, mainly through carbon sequestration (VijayaVenkataRaman et al., 2012), the use of renewable energy sources (Panwar et al., 2011), and the improvement of energy efficiency in processes and buildings (Huesemann, 2006). In contrast, much less work has been devoted to warming mitigation at a macroeconomic level. There are very few works in the

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literature that deal with this topic (Asafu-Adjaye and Mahadevan, 2013), and almost all of them lack a systematic approach for identifying economic actions leading to environmental savings.

In the area of macroeconomics, input output models (Leontief, 1936) provide an exhaustive description of the economic transactions between final consumers and productive sectors in complex trade networks. Input output models have been widely applied to diverse fields over the last four decades (Miller and Blair, 2009) in order to disclose complex connections between economic sectors and nations. One of the main advantages of input output models is that, in addition to revealing the macroeconomic structure of an economy, they can assess the environmental loads using "pollution intensity" vectors associated with the production technologies. This allows translating the economic output of each sector into tangible environmental loads (e.g. greenhouse gas energy related emissions, energy expenditure, and/or consumption of natural resources).

Environmentally extended input output (EEIO) models are flexible, transparent and accurate, which makes them quite appealing for conducting environmental assessment studies (McKenzie and Durango-Cohen, 2010). The very first approaches based on EEIO models that assessed environmental loads (Leontief, 1970; Leontief and Ford, 1972) focused their attention on quantifying air emissions. EEIO models were later applied to study energy related emissions in different areas, including the estimation of the level and composition of greenhouse gas emissions as a function of the final demand of the economies (Butnar and Llop, 2007; Tarancón and del Rio, 2007); the assessment of CO_2 emissions related to specific sectors and/or regions (Alcántara and Padilla, 2009; Wiedmann et al., 2010; Zheng et al., 2007); the assessment of the CO_2 emissions embodied in international trade (Davis and Caldeira, 2010; Davis et al., 2011; Hertwich and Peters, 2009; Lenzen et al., 2004; Peters et al., 2011; Wiebe et al., 2012a, 2012b); and the assessment of other toxic emissions to air (e.g. sulphur oxides, nitrogen oxides, ammonia, particulate matter and other hazardous materials) (Chang et al., 2010; Roca and Serrano, 2007).

The approaches described above provide valuable quantitative information on the anthropogenic environmental loads of economic activities, but offer no guidelines on how to reduce such environmental pressures. Some authors have taken one step further on the application of EEIO models and have used them to identify aprioristic strategies leading to greenhouse gas emissions reductions. These strategies are based on readjusting the economic flows so as to minimize the associated impact (Baiocchi and Minx, 2010; Facanha and Horvath, 2007; Golub and Strukova, 2004; Rosenblum et al., 2000). Other works have studied the implications of alternative environmental policies and future economic scenarios on global warming mitigation (Acquaye and Duffy, 2010; Acquaye et al., 2012; Barrett and Scott, 2012; Bright et al., 2010; Llop and Pié, 2008). Unfortunately, the aforementioned studies are based on a "what if" analysis. That is, they explore only a set of scenarios defined beforehand, which restricts the analysis to a reduced number of alternatives. This type of approaches may eventually result in suboptimal solutions that do not fully exploit the capabilities of EEIO models.

A possible manner to overcome such limitation consists on integrating systematic optimization techniques with EEIO models. In particular, linear programming is an optimization approach well suited to minimize the environmental impact of different economic activities in a systematic manner. Linear programming models have been already coupled with input output analysis for solving environmental problems (Vogstad, 2009). Numerous approaches coupling optimization and EEIO models are limited to the optimization of one single objective; such as the minimization of air emissions in a waste water plant (Lin, 2011); the minimization of CO_2 emissions in household insulation, (Hondo et al., 2006); the maximization of the eco efficiency of a waste management system (Kondo and Nakamura, 2005), or the minimization of the costs given a set of alternative technologies (Duchin and Lange, 1995). Other studies have combined EEIO models with multi-objective optimization to simultaneously optimize environmental and economic objectives. This latter approach has been applied to the economies of Taiwan (Hsu and Chou, 2000), Korea (Cho, 1999), Portugal (Oliveira and Antunes, 2004), Greece (Hristu-Varsakelis et al., 2010), Spain (San-Cristobal, 2012) and Japan (Lin, 2011).

This paper presents a systematic multi-objective optimization approach for simultaneously minimizing the global warming potential (assessed through a life cycle assessment methodology) and maximizing the total economic output of the European Union (EU-25). The calculations are performed using an EEIO model based on a Comprehensive Environmental Data Archive-EU25 ($CEDA_{EU25}$) database (Huppes et al., 2006; Heijungs et al., 2006), which considers 487 sectors (including household activities) for the EU-25 economy in 2006. The use of a highly disaggregated EEIO model allows identifying specific economic activities that are ultimately responsible for the overall environmental impact. In addition, the database incorporates environmental information quantified according to life cycle assessment (LCA) principles. Note that LCA-based EEIO models cover the upstream production stages, thereby avoiding the limitations imposed by conventional system boundary selection (Lenzen, 2001). The integration of LCA and EEIO models with systematic linear programming methods allows for the systematic generation and assessment of a very large number of alternatives that could potentially lead to significant environmental savings. Moreover, EEIO models require less input data than equilibrium models (e.g. product prices), yet they provide valuable information into the economic flows between industrial sectors along with the associated environmental impact.

To the best of our knowledge, this is the first contribution that applies multi-objective optimization to input output models of the whole European Union economy. There are few works that follow a similar integrated approach (i.e., multi-objective optimization applied to EEIO models), but they typically restrict the analysis to single countries or small regions, and in addition to this, they tend to employ highly aggregated data that provides little information on the ultimate source of impact. Furthermore, in this article we present a detailed study of the extent to which the satisfaction of the demand of a single sector (rather than the economic activities performed by a single sector itself) contribute to the total impact. This type of analysis is typically missing in the aforementioned articles. Our analysis allows identifying sectors with low direct greenhouse gas emissions but large indirect ones. This valuable information should be taken into account when formulating more effective environmental policies.

The outline of this article is as follows. Section 2 explains the methodology that we followed, and is divided into two subsections. In Section 2.1 we briefly introduce the EEIO models, focusing on the EU-25 economy in 2006. Then, in Section 2.2 we formally state the multi-objective optimization problem that aims to minimize the greenhouse gas emissions while simultaneously maximizing the economic output of the EU-25 economy. The corresponding linear programming formulation then follows. In Section 3 we present a preliminary analysis of the EU-25's EEIO model based on both a production-based and a consumption-based perspective. We also present in this section the results of the multi-objective optimization approach. Section 4 discusses the results obtained and the main policy implications. The main conclusions drawn from the results are finally presented.