Applied Energy 145 (2015) 234–245

Contents lists available at ScienceDirect

Applied Energy

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

Combination of equilibrium models and hybrid *life cycle-input–output* analysis to predict the environmental impacts of energy policy scenarios

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HIGHLIGHTS

- The environmental impacts of two energy policy scenarios in Luxembourg are assessed.
- Computable General Equilibrium (CGE) and Partial Equilibrium (PE) models are used.
- Results from coupling of CGE and PE are integrated in hybrid Life Cycle Assessment.
- Impacts due to energy related production and imports are likely to grow over time.
- Carbon mitigation policies seem to not substantially decrease the impacts' trend.

ARTICLE INFO

Article history:
Received 11 August 2014
Received in revised form 16 January 2015
Accepted 2 February 2015
Available online 3 March 2015

Keywords:
Computable General Equilibrium model
Partial Equilibrium model
Energy policy
Life Cycle Assessment
Consequential
Input–Output

ABSTRACT

Nowadays, many countries adopt an active agenda to mitigate the impact of greenhouse gas emissions by moving towards less polluting energy generation technologies. The environmental costs, directly or indirectly generated to achieve such a challenging objective, remain however largely underexplored. Until now, research has focused either on pure economic approaches such as Computable General Equilibrium (CGE) and partial equilibrium (PE) models, or on (physical) energy supply scenarios. These latter could be used to evaluate the environmental impacts of various energy saving or cleaner technologies via Life Cycle Assessment (LCA) methodology. These modelling efforts have, however, been pursued in isolation, without exploring the possible complementarities and synergies. In this study, we have undertaken a practical combination of these approaches into a common framework: on the one hand, by coupling a CGE with a PE model, and, on the other hand, by linking the outcomes from the coupling with a hybrid input–output–process based life cycle inventory. The methodological framework aimed at assessing the environmental consequences of two energy policy scenarios in Luxembourg between 2010 and 2025.

The study highlights the potential of coupling CGE and PE models but also the related methodological difficulties (e.g. small number of available technologies in Luxembourg, intrinsic limitations of the two approaches, etc.). The assessment shows both environmental synergies and trade-offs due to the implementation of energy policies. For example, despite the changes in technologies towards the reduction of greenhouse gas emissions, only marginal improvements are observed in the climate change mitigation scenario as compared to the Business-As-Usual. The energy related production and imports are indeed expected to increase over time and represent a large contribution to the country's impacts. Interestingly, side effects on other impacts than climate change or fossil resource depletion (e.g. ionising radiation and water depletion) may also occur mainly due to the use of nuclear energy in neighbouring countries.

1. Introduction

Nowadays energy supply comprises an essential component of economic, energy and environmental landscape that is exacerbated by the growing scarcity of fossil fuels and societal dependence on these resources. Many countries have developed energy policies to address the global challenge of mitigating current and future environmental impacts due to climate change [1]. This concern is particularly important for small and highly developed countries,

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http://dx.doi.org/10.1016/j.apenergy.2015.02.007
0306-2619/

Nomenclature

Abbreviation

AoP	Area of Protection
BAU	Business-As-Usual
CC	Climate Change
CED	Cumulative Energy Demand
CGE	Computable General Equilibrium
DALY	Disability-Adjusted Life Year
EEIO	Environmentally-Extended Input-Output
ETEM	Energy Techno-Economic Model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GHGr	Greenhouse Gas Emissions Reduction
IO	Input-Output
KLEM	Capital-Labour-Energy-Materials
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LU	Land use
NMVOC	Non-Methane Volatile Organic Compounds
PE	Partial Equilibrium
WD	Water Depletion
WIOD	World Input-Output Database

like Luxembourg, which do not own sufficient energy carriers and primary resources and depend on imported fossil resources to sustain their socio-economic welfare and technological development [2].

Luxembourg's greenhouse gas (GHG) emissions profile highlights the significant contribution of the energy sector, covering about 90% of the total GHGs emissions in 2011, and the increase of the emissions from energy-producing industries and transportation as compared to the 1990 levels [3]. Moreover, current energy policies in Luxembourg focus on improving the energy efficiency of buildings through the introduction of energy performance certificates [1]. To fulfil the 20/20/20 targets set by the European Union in 2009 (EC, 2009), Luxembourg's energy mix should include by 2020 at least 20% of renewable sources, mainly biomass-based [4]. Nonetheless, the actual environmental consequences related to the implementation of new energy supply strategies in the country can no longer be evaluated without considering side-effects. For example, in Vázquez-Rowe et al. [4], the use of maize-based biofuels to reach the 20% of renewable energy in Luxembourg was observed to increase indirect GHG emissions, land use and fossil depletion, also due to important shifts in the import/export of agricultural products.

The latter study was based on Life Cycle Assessment (LCA) [5], which is one of the most commonly applied methods to evaluate the environmental impacts of goods and services over their entire supply-chain. In particular, Vázquez-Rowe et al. [4] applied the consequential LCA perspective, aiming at describing the indirect and direct environmental consequences of (marginal or large scale) changes induced by strategic decisions and actions [6], such as those driven by energy policies. Consequential LCA has still not achieved a full methodological consensus, mainly due to the different computational approaches proposed by scholars in the recent years. These have stimulated the development of alternative modelling techniques for impact scenarios and technologies implementation [7,6]. In this regard, vast literature already presented cases of evaluation of energy supply scenarios based on LCA. For example, Koskela et al. [8], Brown et al. [9] and Dale et al. [10] focused on the assessment of production technologies for a given country and timeframe (Estonia for 2020, USA for 2055 and Brazil for 2040, respectively). The former authors analysed LCA-based scenarios according to strategic guidelines (e.g. 10% of renewable energy), but without changing the modelling (only adjusting plants efficiency to consider technological improvement). The two latter studies relied on cost optimisation models to determine the effects of electricity supply scenarios on the use of production technologies and the related environmental impacts on air quality and GHG emissions.

These studies show the flexibility and pertinence of LCA in bottom-up analyses. However, detailed datasets are needed to model the life cycle inventory (LCI) of current and future technologies with a significant degree of accuracy. Furthermore, the granularity of the LCA system boundary is usually limited, as process-LCA can fail in providing consistent evaluations of the environmental consequences to other economic sectors beyond energy. To cope with this inventory truncation problem, Dandres et al. [11] discussed on the potential benefits of linking Partial Equilibrium (PE) or Computable General Equilibrium (CGE) models to LCA and eventually combining them. They argued that such a link with LCA can improve the accuracy of inventory for specific evolving technologies in LCA, while enhancing the methodology to conduct consequential assessments of energy policies. In this regard, extensive literature demonstrates the feasibility and effectiveness of using CGE or PE models to simulate future environmental burdens, although the proposed analyses were typically limited to the estimate of future carbon emissions without considering a full life cycle perspective [12–17]. Interestingly, Input–Output (IO) models were often used in combination with CGE or PE models, either as alternative to LCA or to strength the overall LCI for some specific technologies [18–20].

Lee and co-authors [21] and Mischke and Karlsson [22] comprehensively illustrate the *pros* and *cons* of using CGE, PE, LCA and IO models to predict the environmental impacts at country's scale. On the one hand, CGE models are considered beneficial to provide with information to simulate the response of the full economy to certain policy scenarios, incorporating price changes at the level, for example, of IO tables. On the other hand, PE models can provide detailed data about demand and supply response to shocks in specific economic sector (e.g., energy sector) with possible links to LCA via modification of the LCI datasets. This latter approach typically combines Environmentally-Extended IO (EEIO) modelling for hybridisation with LCA, in order to achieve mutual benefits, among which avoiding system boundary truncation and increasing process evaluation detail [23–26]. Despite IO tables may lead to several assumptions and limitations (see e.g. [27]), their flexible and standardised structure may allow several adjustments and extensions, for example using outputs from PE and CGE models.

While it is common practice to use CGE or PE to forecast environmental impacts (in particular with regard to climate change) and assess mitigation scenarios, to the best of our knowledge there are no studies that explicitly address the improvement of consequential LCA by using a combination of CGE and PE. Therefore, the novelty of this paper consists in i) the development of a coupling between CGE and PE models in order to simulate future economic and energy scenarios, which in turn can lead to ii) the implementation of policy effects (changes in the economic/technological structure) in a hybrid LCA framework to assess future environmental impacts. More specifically, the objective is to assess the environmental consequences of an energy policy for GHG reduc-