Energy xxx (2016) 1–12

Contents lists available at ScienceDirect

Energy

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

Overlooked impacts of electricity expansion optimisation modelling: The life cycle side of the story

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ARTICLE INFO

Article history:
Received 11 September 2015
Received in revised form
27 January 2016
Accepted 14 March 2016
Available online xxx

Keywords:
Energy modelling optimisation
MESSAGE
Climate change mitigation
Life cycle assessment
Carbon tax
Brazil

ABSTRACT

This work evaluates implications of incorporating LCA-GHG (life cycle assessment of GHG emissions) into the optimisation of the power generation mix of Brazil through 2050, under baseline and low-carbon scenarios. Furthermore, this work assesses the impacts of enacting a tax on LCA-GHG emissions as a strategy to mitigate climate change. To this end, a model that integrates regional life cycle data with optimised energy scenarios was developed using the MESSAGE-Brazil integrated model. Following a baseline trend, the power sector in Brazil would increasingly rely on conventional coal technologies. GHG emissions from the power sector in 2050 are expected to increase 15-fold. When enacting a tax on direct-carbon emissions, advanced coal and onshore wind technologies become competitive. GHG emissions peak at 2025 and decrease afterwards, reaching an emission level 40% lower in 2050 than that of 2010. However, if impacts were evaluated through the entire life cycle of power supply systems, LCA-GHG emissions would be 50% higher in 2050 than in 2010. This is due to loads associated with the construction of plant infrastructures and extraction and processing of fossil fuel resources. Thus, taxes might not be as effective in tackling GHG emissions as shown by past studies, if they are only applied to direct emissions.

1. Introduction

Brazil boasts one of the world's largest shares of renewable energies in the power generation portfolio, accounting for more than 78% share coming from non-fossil resources [9]. Nonetheless, this relatively environmentally friendly profile is currently shifting to another direction. Brazil's socio-economic growth over the past years has ramped up energy consumption, which is projected to increase by some 50% over the next decades. Following a business-as-usual scenario, a considerable portion of the new baseload power will be supplied by fossil fuels, and, to some extent, by advanced renewable energy systems such as wind and PV (photovoltaic) solar power [23].

A major challenge in developing the expansion of the power generation system is how to define an optimal pathway that guarantees energy security of supply and complies with climate change mitigation objectives, without undermining economic development and social inclusiveness. In order to expand the power generation system several factors should, therefore, be taken into consideration, including minimisation of total generation costs and reduction of GHG emissions.

In the literature, several studies have applied optimisation energy planning models, aiming at forecasting the Brazilian energy supply mix considering these factors. For instance, Borba et al. [2] estimated the potential for GHG emission reduction of industrial, transportation and petroleum sectors and associated abatment costs and evaluated energy policies to achieve climate change mitigation goals. Nogueira et al. [29] evaluated the effects of different market-based mechanisms in the implementation of CCS (carbon capture and storage) technologies in thermal power plants in Brazil up to 2050. Recently, Lucena et al. [23] compared different energy-economic assessment models to analyse the implications of carbon taxes and carbon abatement targets on the Brazilian energy system in terms of energy mix and GHG emissions. While relevant to the field, these studies, with a few exceptions [7], only account for the direct GHG emissions of energy systems, which clearly

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http://dx.doi.org/10.1016/j.energy.2016.03.062

benefit renewable energies, as they have minimal direct emissions [30]. Nonetheless, the LCA-GHG (life cycle assessment of GHG) emissions should not be neglected, as renewable energies may require energy intensive materials and indirect consumption of fossil fuels in their material life cycle [34].

In order to fill this gap, this work evaluates the implications of LCA-GHG emissions in the optimisation of Brazil's power generation mix in a 2050 horizon, under baseline and low-carbon scenarios considering a range of costs and carbon constrains. Furthermore, this work assesses the impacts of enacting a tax on LCA-GHG emissions from the power sector as a market-based mechanism strategy to mitigate climate change. To this end, a robust model has been developed by integrating regional life cycle data of electricity generation systems in Brazil with optimised energy scenarios developed by using MESSAGE (Model for Energy Supply System Alternatives and their General Environmental Impact) tailored to a Brazilian context, the so called MESSAGE-Brazil model [29]. The novelty of the paper is in the comparison of the effects of internalizing carbon costs on electricity production considering or not the life cycle emissions. While previous studies forecasted energy expansion scenarios under perfect foresight conditions and carbon constrains, there is still the need to evaluate the effects of LCA-GHG emissions in the integrated energy expansion optimisation scenarios.

2. Analytical framework

To assess the optimisation of the power generation mix and the implications of taxing direct- and LCA-GHG emissions, the present research is organised in three methodological stages as shown in Fig. 1, entailing: (i) characterisation and parameterisation of power generation systems, (ii) developing a database of LCA-GHG emissions, and (iii) model simulation of optimal electricity supply mixes accounting for direct- and LCA-GHG emissions. The following sections describe each of these stages in detail.

2.1. Characterisation and parameterisation of energy systems

Table 1 displays technical parameters of power generation technologies considered in this study. Overall, it includes 12 primary and secondary energy sources, comprising uranium, fossil fuels (endogenous and imported coal, natural gas, and oil), hydrogen, and renewables (sugarcane bagasse, ethanol, woody wastes, hydropower, wind, and solar). The technological chains encompass nuclear PWR (pressurized water reactor) plants, thermal power plants fired by oil, coal (pulverized – PC, fluidized-bed – FBC – and integrated gasification combined cycle – IGCC) and natural gas (open and combined cycle), as well as renewable-based technologies, such as small-, mid- and large-reservoir hydropower plants, thermal power plants burning sugarcane bagasse and other woody wastes, onshore and offshore wind farms, solar-PV and CSP (concentrated solar power) facilities and decentralised Otto-engine generators powered with conventional sugarcane ethanol. CCS (Carbon capture and storage) technologies have also been taken into consideration in fossil fuel-based and biomass-based thermal power plants as feasible end-of-pipe mitigation strategies. The technological foresight has been conducted from a baseline year (2010) to a 2050 horizon. This is consistent with previous studies about Brazil's energy sector modelling, for instance Nogueira et al. [29], Lucena et al. [23], and Lima et al. [21]. Also, this analysis relies on techno-economic forecasts of the EIA Energy Technology Perspectives report [15] and economic parameters of the National Energy Agency Energy forecast [10], both developed until a 2050 timeline. A detailed characterisation of evaluated energy systems is presented in Appendix A.

2.2. Database of LCA-GHG emissions

In this study, the database of LCA-GHG emissions has been developed by applying an attributional life cycle assessment (ALCA),[1] following the ISO 14040-44 guidelines [19]. The selected functional unit is the electricity supplied to end-users to fulfill their yearly demand in TWh. Total GHG emissions have been calculated as the sum of the power generation life cycle sub-systems, including both upstream (extraction of fuels and raw materials, fuel processing and transportation) and downstream processes (operation of power plants and transmission and distribution to the national grid up to end-users). The material life cycle, the so-called "Cradle-to-Gate" cycle, has also been taken into account, comprising the construction of the thermal power plant infrastructure and the manufacture of material requirements for the construction of renewable power generation facilities, namely hydro dams, windmills, solar-PV panels and CSP parabolic troughs. Thus, the "Cradle-to-Gate" impacts are exclusively limited to the plant construction period, which varies according to the energy technological chains. Nonetheless, impacts from the material life cycle have been *levelised* uniformly through the entire operation period of the plant during its lifetime. Although this simplification does not represent truly the environmental burdens because emissions depend upon the choice of multi-gas equivalency metric and climate impact time horizon (see Ref. [27]), this is a common practice in life cycle assessment studies [35]. As this analysis compares different scenarios, rather than evaluating in absolute terms the environmental impacts of a single technology, using the same basis of comparision is sufficient to provide reliable results. Fig. 2 shows the flow diagram of the LCA steps conducted in the analysis.

Although the Brazilian national electric system is represented in the model by three regional divisions, namely North, Northeast and Central-South-Southeast, the LCA database does not take into account the regional specificities of these sub-systems. It rather includes national averages of transmission and distribution losses, conversion efficiency of processes and technical characteristics of plants, as described in Table 1.

The LCA-GHG was developed by simulating input and output streams that describe power generation processes with SimaPro 8.0.1® model architecture [12]. SimaPro is an LCA software that allows users to customise inventory libraries of all stages of the life cycle (used materials, fuel extraction, processing and delivery). The inventory data of greenhouse gases (CO_2, CH_4, and N_2O) were collected from EcoInvent database [31], governmental agencies [1,9] and relevant literature [5,6,24,33]. Then, the individual greenhouse gases were aggregated into CO_2e (carbon dioxide equivalent) emissions in accordance to the GWP (Global Warming Potential) in a time horizon of 100 years as described by IPCC in its 5th assessment report [28].[2]

Table 2 summarises the CO_2e emissions of power supply systems projected in a 2050 horizon, expressed in gCO_2e/kWh, of power generation technologies during their full life cycle, i.e., emissions from the upstream, infrastructure and downstream

[1] In the literature, LCA is classified in two different types: attributional and consequential. The Attributional LCA evaluates the average impacts of a system without assessing the implications beyond its system boundary. In the context of power generation systems, this approach is followed when assessing impacts of average power grid mixes. The Consequential LCA, on the other hand, describes the effects of changes introduced by a new system external to LCA boundaries. This approach is followed when assessing, for instance, the generation of marginal power.

[2] Carbon dioxide equivalent emissions (CO_2e) are calculated by the following expression: $CO_2e = CO_2 + 34 \cdot CH_4 + 298 \cdot N_2O$, according to the GWP factors suggested by IPCC in its 5th assessment report [28].