Journal of Environmental Management 219 (2018) 208–217

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Water conservation implications for decarbonizing non-electric energy supply: A hybrid life-cycle analysis

Shiyuan Liu[a,b], Can Wang[a,b,*], Lei Shi[a], Wenjia Cai[b], Lixiao Zhang[c]

[a] State Key Joint Laboratory of Environment Simulation and Pollution Control (SKLESPC), School of Environment, Tsinghua University, Beijing 100084, China
[b] Ministry of Education Key Laboratory for Earth System Modelling, Department of Earth System Science, Tsinghua University, Beijing 100084, China
[c] State Key Joint Laboratory of Environment Simulation and Pollution Control (SKLESPC), School of Environment, Beijing Normal University, Beijing 100875, China

ARTICLE INFO

Keywords:
Water-energy nexus
Transport energy
Heating energy
Hybrid LCA

ABSTRACT

Low-carbon transition in the non-electric energy sector, which includes transport and heating energy, is necessary for achieving the 2 °C target. Meanwhile, as non-electric energy accounts for over 60% of total water consumption in the energy supply sector, it is vital to understand future water trends in the context of decarbonization. However, few studies have focused on life-cycle water impacts for non-electric energy; besides, applying conventional LCA methodology to assess non-electric energy has limitations. In this paper, a Multi-Regional Hybrid Life-Cycle Assessment (MRHLCA) model is built to assess total CO_2 emissions and water consumption of 6 non-electric energy technologies – transport energy from biofuel and gasoline, heat supply from natural gas, biogas, coal, and residual biomass, within 7 major emitting economies. We find that a shift to natural gas and residual biomass heating can help economies reduce 14–65% CO_2 and save more than 21% water. However, developed and developing economies should take differentiated technical strategies. Then we apply scenarios from IMAGE model to demonstrate that if economies take cost-effective 2 °C pathways, the water conservation synergy for the whole energy supply sector, including electricity, can also be achieved.

1. Introduction

Water use from energy supply sector is one of the most significant sources of global water consumption (IEA, 2016). It is vital to understand the potential water impacts during decarbonization of energy supply sector, as well as their implications and trade-offs (Berndes, 2002; IEA, 2012). Numerous studies have been carried out to discuss transition impacts of power sectors (e.g., Cavallaro et al., 2018; Dolter and Rivers, 2018; Huang et al., 2017; Macknick et al., 2012; Ou et al., 2016; Wang et al., 2017; Zheng et al., 2016). Wan et al. (2016) find that water consumption of power sector commonly increases under NDCs (Nationally Determined Contributions) mitigation scenarios, Kyle et al. (2013) finds that influence of emerging technologies on global water withdrawal is limited under large-scale electrification scenario. Acquaye et al. (2017) reveal that among EU27, G7 and BIC nations, countries with high Water Stress Risk also have the highest water-intensive electricity industries. However, few studies have focused on water implication for decarbonization in non-electric energy. They provide about 78% of global energy supply and account for 58% of energy-related GHG emissions (Krey et al., 2014). It is impossible to achieve the long-term 2 °C target without the mitigation efforts of the non-electric energy in any of IAMs (Integrated Assessment Models). Therefore, policymakers are paying more attention to low-carbon transition in non-electric energy. Brazil plans to increase biofuels supply to 18% of the country's energy mix by 2030 to meet their NDC targets (Leticia, 2016). China also announced to promote bioethanol all across the country by 2020 (Economic Daily, 2017). Meanwhile, non-electric energy is also a significant water consumer, which accounts for over 62% of total water consumption from energy supply sector (IEA, 2016). Most of the direct water is consumed in cultivating energy crops, cooling, and mining (Spang et al., 2014), while substantial indirect water is embedded in upstream supply chains, and this is induced by other industries' inputs through input-output relationship. Studies have suggested that some non-electric products, such as the US bioethanol fuels, contain a large proportion of indirect water use (Chiu et al., 2009). How decarbonization of non-electric energy will influence water demands, and whether there is a chance to achieve synergy of carbon reduction and water conservation remains unclear. Therefore, it is necessary to consider non-electric sector in evaluating the impacts of decarbonization of whole energy supply sector on the water system.

Non-electric energy mainly contains transport energy and heating energy. In the end-use sectors, transport sector is the largest CO_2

* Corresponding author. School of Environment, Tsinghua University, Beijing 100084, China.
E-mail address: canwang@tsinghua.edu.cn (C. Wang).

https://doi.org/10.1016/j.jenvman.2018.04.119
Received 15 December 2017; Received in revised form 27 April 2018; Accepted 30 April 2018

emitter in many economies (IEA, 2016). Power for vehicle primarily comes from fossil gasoline, biofuel, and natural gas, etc. The demand for heat energy occupies 52% of global final energy demands (IEA, 2016), and penetrates throughout the industry, construction, household and other sectors. Heat supply comes mainly from fossil fuels like coal and natural gas, and renewables like residual biomass and solar thermal energy, etc. Studies that discuss transition impacts of non-electric sectors, usually classify them by final demand, such as building, industry or household (Cai et al., 2015; Li and Colombier, 2009; Eurostat, 2017). However, different end-use sectors in a single region tend to have close connections on energy supply structure, for example, industry and household sector can share same heat supply source in a single region (Darby, 2017), and decarbonizing industry sector also affects energy structure in household sector (You et al., 2017). Besides, under a relatively fixed carbon budget in the context of climate change mitigation, energy supply for different sectors in one economy has trade-off relationship (IEA, 2012; Jiang et al., 2015; Yang et al., 2018). Therefore, it is necessary to regard the entire energy supply sector of an economy as a single sector for studying the impacts of low-carbon transition.

One of the critical points in studying the water-energy issue is compiling life cycle inventories (LCIs) for technologies. Most studies use “bottom-up” approaches to calculate water footprints. Lecksiwilai et al. (2017) conducted a conventional LCA for freshwater use of biofuel production, and Fricko et al. (2016) assessed water use of thermoelectric power plants by adding a function of the thermal conversion efficiency in the MESSAGE model. Yet these studies focus more on direct water use rather than indirect use. Usually, inventories calculated by Process Life-Cycle Analysis (PLCA) can only account for direct water and part of indirect water footprints, due to the artificially defined system boundary (defined as cut-off error) (Lenzen, 2002; Menzies et al., 2007). The cut-off error for energy products is commonly between 20 and 50% of the total environmental impacts (Lenzen, 2000); in some cases, indirect inventory can contribute 50–60% of total impacts (Wiedmann et al., 2011). Some other studies applied “top-down” economic models to draw the full LCIs. Zhang and Anadon (2014) used environmental extended MRIO (Multi-Regional Input–Output) model to calculate the water footprint of energy supply sector in China, and found that uneven spatial distribution of energy-related consumptive water exists in China. Watanabe et al. (2016) applied Input-Output approach to demonstrate the economic and environmental benefits of ethanol production in Brazil. IO approach has a complete system boundary since the entire economic activities of an economy are contained. However, limited by statistical caliber of the Input-Output table, these studies cannot distinguish different non-electric energy from IO table, significant allocation errors are inevitable in sectoral disaggregation (Acquaye et al., 2017; Crawford, 2008; Palma-Rojas et al., 2017). Hybrid LCA is playing an increasingly important role in calculating the embodied resource use (e.g. Clark and Chester, 2016; Feng et al., 2014; Lindner and Guan, 2014) and environmental impacts (e.g. Bush et al., 2014; Hertwich et al., 2014; Martínez-Corona et al., 2017; Palma-Rojas et al., 2017) associated with specific product systems. It combines PLCA and IO in a consistent mathematical framework (Heijungs et al., 2006), in which the PLCA component systematically establish the direct environmental impacts associated with entire supply chain within the system boundary, and the IO component is able to capture indirect environmental flows from outside the process system boundary. Hybridizing bottom-up process LCA into a top-down IOA means to connect economic IO table with physical supply chain at upstream and downstream cut-offs, reflecting interactions between the energy supply sector and the rest of economy more comprehensively (Pairotti et al., 2015; Suh, 2003).

This study applied a multi-regional hybrid LCA framework (Gibon et al., 2015; Suh and Huppes, 2005) to calculate the life-cycle water consumption and CO_2 emission of 6 non-electric energy production technologies, in 7 major emitting economies (including Brazil, China, India, EU27, Japan, Russia, and the US). These 6 energy technologies represent major non-electric energy supply technologies involved in the low-carbon transition, which includes 2 transport fuels and 4 heating products. These 7 economies represent the largest economies in developing and developed regions; they also contribute near 70% of global GHG emission (2013 data) (WRI, 2015). Scenario analysis is used to discuss water implication under 2-degree pathways of whole energy supply sector in each economy.

2. Methodology

2.1. Global integrated hybrid LCA model

The basic layout of the hybrid LCA model framework is depicted in Eq. (1) and Eq. (2). Economic connections among 7 regions and the rest of world (ROW) are represented with supply and use tables (SUT) as well as trade tables with 224 sectors, respectively.

The general formula of the integrated hybrid model can be expressed in Eq. (1).

$$W_{hybrid} = \begin{bmatrix} E_p & 0 \\ 0 & E_{io} \end{bmatrix} \begin{bmatrix} A_p & -C_d \\ -C_u & I - A_{io} \end{bmatrix}^{-1} \begin{bmatrix} f_p \\ 0 \end{bmatrix} \tag{1}$$

Where W_{hybrid} denotes total water consumption; E_p denotes the process inventory environmental extension matrix, E_{io} denotes IO environmental extension matrix. In a product system, output of a process serve as inputs supporting the production of a new output, relations between physical processes are described by the multi-regional direct requirements matrix A_p, which is a 4115 products by 4115 processes matrix. Internal linkages within the IO background system is represented by A_{io} technology coefficient matrix, which is a global multi-regional IO table. C_u is the representation of upstream monetary cut-off flows from corresponding economic sectors to the foreground process system, and C_d is the matrix of downstream physical cut-offs from process system to the IO system, C_d can be set to zero (Suh, 2004) Ultimately, all activities within processes and sectors operate to satisfy final demand given by column matrix $\begin{bmatrix} f_p \\ 0 \end{bmatrix}$.

Furthermore, the direct requirement matrix A_p is composed of three types of sub-modules, as Eq. (2) indicates:

$$Ap = \begin{bmatrix} A_{ff} & 0 \\ A_{bf} & A_{bb} \end{bmatrix} \tag{2}$$

Where A_{ff} describes the linkages among processes in the foreground system, which is the specific manufacturing processes of 6 technologies in 7 regions, which is a 42 × 42 matrix. A_{bf} describes the inputs to foreground system from background LCA system, which is defined as the whole interlinked industrial supply chains that comprise the LCA database, A_{bb} describes the internal linages within the LCA background system.

2.2. Technology selection

Choosing proper process lines is crucial in this study, 6 types of non-electric energy technologies are selected, which include 2 transport fuels, and 4 heating fuels. They cover over 70% of non-electric energy supply in these economies in 2010 (Kriegler et al., 2014), and represent non-electric energies involved in the low-carbon transition. According to their historical production, We select the most productive process lines as typical processes, representing localized characteristics of this type of energy production, detail technical information is listed in Table S1. It should be noted that we only focus on technologies in the mature stage, potential emerging technology like CCS, shale gas is not discussed here; besides, we only discuss decarbonization within non-electric energy sector, technology that helps electrify energy structure, such as electric vehicles is beyond our scope. In addition, 7 economies