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The carbon neutrality of electricity generation from woody biomass and coal, a critical comparative evaluation

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HIGHLIGHTS

- A methodology for synchronized life cycle analysis is introduced in this study.
- This study confirms that woody biomass is not a carbon neutral source of energy.
- Coal can become carbon neutral when synchronized with the biogenic forest system.
- The use of woody biomass for energy production can negatively impact the environment.

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ABSTRACT

Woody biomass has been considered as a low carbon or carbon neutral source of energy when viewed from the life cycle perspective. Analytical techniques generally assume that there is a connection between the biogenic forest system and the anthropogenic biomass electricity generation system. In the conventional approach, carbon emission from the biomass electricity generation system assumes to be completely sequestered by the replenishment of the forest. There are fundamental issues with the assumption of complete sequestration. These issues are caused by critical errors in formulating the system and boundary conditions. In the attempt to detect and resolve these errors, the concept of partial temporal boundary for synchronizing interconnected systems over a common life cycle is introduced to facilitate accurate formulation of the boundary conditions. Findings from the case studies demonstrate that woody biomass is not carbon neutral. Instead, coal may be considered as a carbon neutral source of energy when connected to the biogenic forest system. This study concludes that woody biomass can negatively impact the global climate policy developments if the current misunderstanding continues. Furthermore, managed rotation for woody biomass production can cause harmful impacts to the larger environmental and ecological spheres by introducing constant disturbance to the biogenic forest system. As such, it is doubtful whether woody biomass is a sustainable source of energy for addressing global climate targets.

1. Introduction

In the bioenergy roadmap published by the International Energy Agency (IEA) [1], deployment of advanced biomass cook stoves and biogas systems can provide access to clean energy to some 320 million households in developing countries by 2030. By 2050, bioenergy could supply 7.5% of world electricity generation, thereby contributing to 1.3 Gt-CO_2 savings per year. In the fifth assessment report [2], the Intergovernmental Panel on Climate Change (IPCC) outlined an ambitious “zero emission by 2100” target in which renewable energy would play an important role. With the electricity sector accounting for more than half of the world’s carbon emissions [3], there is an increasing number of studies focusing on the life cycle carbon emission of electricity generation [4]. Among these studies, woody biomass is generally considered as a low carbon or carbon neutral source of energy when compared with fossil fuels, such as coal and natural gas. However, there are conditions for biomass to achieve carbon neutral as seen in [5]. According to the US Environmental Protection Agency [6], the carbon neutrality of woody biomass depends on the feedstock’s production and consumption cycle, and the life cycle analysis (LCA) method used in the evaluation.

In the literature, Heller and others [7] evaluated the life cycle energy and environmental benefits of co-firing willow biomass with coal. The study considered the use of willow biomass as carbon neutral assuming all carbon emissions related to the

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Nomenclature

Abbreviations

IEA	International Energy Agency
LCA	life cycle analysis
IOA	Input-Output Analysis
IPCC	Intergovernmental Panel on Climate Change
PCA	process chain analysis
SC	supercritical
Sub-C	sub-critical
USC	Ultra-Supercritical

Symbols

C_E	system carbon emission due to energy input
C_{Fuel}	carbon emission due to the consumption of power plant fuel
C_{NE}	system carbon emission due to non-energy input
$c_{e,i}$	carbon content of process energy input
c_{Fuel}	carbon content of the fuel consumed by the power plant
$c_{ne,i}$	carbon content of process non-energy input
ELC	amount of electricity generated by the power plant
E_i	process energy input by type (e.g. diesel or electricity)
E_n	total process energy input
E_{sys}	total system energy input
e_i	energy input per unit of product produced
H	gross heating value of the fuel
M_{Fuel}	amount of fuel required by the power plant
NE_i	process non-energy input by type (e.g. concrete, steel, or other materials)
NE_n	total process non-energy input
NE_{sys}	total system non-energy input
ne_i	non-energy input per unit of product produced
P_e	electricity generating capacity of the power plant
p_n	product made by each process of the life cycle system
Q	thermal energy requirement
T	lifetime of the power plant
η_e	overall electricity generation efficiency of the power plant
ϕ	load factor of the power plant

combustion of willow were sequestered by the growth of willow. Perilhon and others [8] conducted an LCA study on two co-generation plants (2 MW and 10 MW) using wood waste. The study showed biomass as a low carbon and low polluting energy source compared with coal. Thakur and others [9] evaluated the change in life cycle energy use and carbon emissions from the combustion of forest residues when the size of the power plant varied from 10 to 300 MW. The study demonstrated that the LCA results are sensitive to the biomass moisture content and the power plant lifetime. Arteaga-Pérez and others [10] and Tsalidis and others [11] studied the life cycle environmental impacts of co-firing coal with forest biomass for electricity generation. Both studies reported that the co-firing with wood pellet can help reduce the overall environmental impacts compared with firing coal alone. In addition, there are other studies related to other aspects of biomass utilization, such as the use of non-woody biomass [12], optimization of biomass supply chain [13–15], social and economic aspects of biomass utilization [16] and thermo-ecological cost evaluation [17].

Studies in the literature generally employs an implicit assumption that the combustion of woody biomass is the same as that of coal. If the sequestration of carbon emission by the replenishment of forest were ignored, the life cycle carbon emission of biomass electricity can become very high. Comparing the findings from the US National Renewable Energy Laboratory [18], Nease and others [19], Chang and others [20], and other studies, the life cycle carbon emission of electricity generation from woody biomass without considering the forest can be comparable to that of coal.

Further observation reveals that the carbon neutrality of woody biomass is closely dependent on the assumed physical and temporal boundaries of the life cycle system. The boundary conditions employed in the conventional approach assumes all carbon emissions released from the biomass electricity generation system are fully sequestered by the replenishment of forest. Although the conventional approach appears intuitive, there are fundamental issues with this approach. These fundamental issues are caused by the erroneous formulation of the physical and temporal boundaries. According to the IEA [21], the temporal boundary signified by the timeframe of CO_2 emission and sequestration is important, but there are practical challenges in choosing an appropriate timeframe of assessment.

In response, the concept of partial temporal boundary for synchronizing interconnected systems over a common life cycle is introduced in Section 2. The resulting methodology can facilitate an accurate formation of the physical and temporal boundaries when connecting the biogenic forest system to the anthropogenic biomass electricity generation system. Case studies are developed by applying the methodology to compare the life cycle carbon emissions of coal and biomass in Section 3. Implications of the findings from the case studies are discussed in Section 4 with conclusions in Section 5.

2. Methodology

There are broadly two approaches in the LCA literature, the Process Chain Analysis (PCA) and the Input-Output Analysis (IOA). PCA is a bottom-up approach that uses engineering and process-specific data. The PCA approach can produce more accurate results [22], but it requires a proper set of cut-off criteria to ensure accuracy [23]. IOA is a top-down approach that considers aggregated flows among economic sectors. Applying the concept of synchronization requires a process driven system representation. Thus, a methodology using the PCA approach is more suitable for the proposed analyses. A PCA methodology can be developed by following the general framework described in the ISO 14040 as seen in [24–26], a computerized simulation tool as seen in [27,28], or the energy balance principle as seen in [29,30].

2.1. Conventional PCA approach

In the conventional PCA approach, a life cycle system comprised of multiple processes can be represented as shown in Fig. 1. In this representation, there is a boundary between the life cycle system and its surroundings. There are energy and non-energy inputs to the system in exchange of energy output, energy loss, and carbon emission released to the surroundings. With reference to the methodology described in [30], each process of the system produces a product to be used by the immediate next process. The transformation of product across the life cycle system assembles the process chain.

Looking beyond the life cycle system, the energy and non-energy inputs are effectively the outputs of other life cycle systems. As such, there is a boundary between the life cycle main system and the life cycle sub-systems (Fig. 2). The sub-systems are responsible for producing inputs to the main system. Furthermore,