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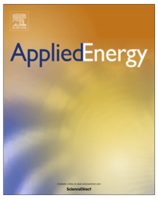

Life cycle assessment of thermal energy production from short-rotation willow biomass in Southern Ontario, Canada

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HIGHLIGHTS

- Environmental impacts of thermal energy from combustion of willow were evaluated.
- Biomass combustion resulted in ~85% reduction of GWP relative to fossil fuels.
- Willow biomass production contributed to most of the life cycle impacts.
- Increasing yields and better management will improve willow energy performance.
- Cleaner combustion technologies will improve willow bioenergy performance.

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ABSTRACT

As part of efforts to address the root causes of climate change and non-renewable resource depletion, many regions in the world are considering sustainable biomass feedstocks for renewable energy production. Prior to making such large-scale shifts in primary energy feedstocks, location-specific research is still needed to understand the environmental impacts and benefits of biomass associated with its many potential applications. The objective of this study was to evaluate environmental and energy impacts associated with generating 1 MJ of thermal energy from direct combustion of short rotation willow (SRW) pellets for 2 purposes: to determine where improvements could be made in the life cycle of SRW bioenergy to reduce impacts, and to compare SRW bioenergy to fossil fuel (light fuel oil and natural gas) for thermal energy. Life cycle assessment (LCA) was conducted using primary data on SRW biomass production collected from field trials at the Guelph Agroforestry site in Guelph, Ontario, Canada, as well as carbon sequestration rates modeled based on local conditions. Results showed that direct combustion of SRW pellets reduced global warming potential (GWP) by almost 85% relative to the fossil fuels. However, relative to fossil fuels, SRW energy had higher impacts in certain categories (e.g. eutrophication and respiratory effects), due to biomass combustion and N inputs (inorganic fertilizer and SRW leaf inputs) for biomass production. Soil nitrous oxide emissions, from the N inputs, dominated the GWP, but a sensitivity analysis showed that soil carbon sequestered by SRW biomass during growth could reduce the GWP by 23%. Pelletizing the SRW biomass prior to combustion affected the energy ratio and accounted for almost 85% of non-renewable energy use in the life cycle of bioenergy. Location-specific factors that affected environmental performance of the bioenergy system included agro-climatic conditions, management practices, and conversion technologies. Nevertheless, most of the impacts associated with SRW thermal energy generation can be minimized through better fertilizer management, by using alternate sources of fertilizer, by improving yields, and by the use of cleaner wood combustion technologies with emissions controls.

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1. Introduction

Wood biomass has been identified globally as a renewable energy feedstock with potential to displace non-renewable fossil fuels, reduce global greenhouse gas (GHG) emissions, promote local and regional energy security, and create new economic opportunities for rural communities [1–3]. Despite its potential benefits, the use of wood biomass energy can result in several environmental and human health issues, including competition with arable land for growing economically-viable wood energy crops [4], increases to short and medium-term greenhouse gas (GHG) emissions relative to fossil fuels [5–7], emission of air pollutants during combustion [8,9], ecological impacts to forest ecosystems from increased harvesting [10,11], and biodiversity impacts related to use of "marginal" land for growing energy crops [12,13]. The potential environmental impacts and benefits are dependent upon the energy conversion technology, the fossil fuel energy being displaced, and the source and type of feedstock used [6,14–17]. Of particular importance in determining environmental performance is the source and type of feedstock, which can include wood fiber residuals and co-products from forestry and sawmill operations, construction and demolition waste, harvesting of standing trees, and perennial short-rotation woody crops. Assessing the environmental impacts of wood biomass feedstock options is therefore important for bioenergy producers and policy makers. Several studies suggest that the use of residuals is environmentally-preferable to harvesting of standing trees [6,18], particularly from a GHG emissions perspective since there is no incremental impact on forest carbon sequestration potential; however, as bioenergy systems are deployed at a larger scale, the demand for forest harvest and sawmill residuals will increase, and the availability and economic viability of accessing alternative sources of residuals will increasingly become a barrier [10,19–22]. The identification of other, sustainable feedstock alternatives is therefore critical for advancing the use of wood biomass energy systems.

Short-rotation woody crops such as willow (Salix spp.) are becoming increasingly attractive as a source of wood biomass feedstock supply [23–25], and could reduce pressure on primary forest harvesting, in addition to providing a sustainable alternative to limited stocks of wood biomass residuals. Short-rotation willow (SRW) has been cultivated as a biomass energy crop in both Europe and North America due to its desirable characteristics such as rapid growth (>15 oven-dried tonnes ha^{-1} year^{-1} on 3- to 4-year rotations over 20–25 years [26], vigorous coppicing ability, ease of propagation, tolerance to high plant density and potential for genetic improvement. Short-rotation willow crops are also associated with many other environmental and socio-economic benefits, such as enhancing biodiversity [27], remediating sites contaminated by various industrial and agricultural wastes [28,29], recycling and managing soil nutrients [30], improving rural farm economies by promoting farm crop diversification and creating an additional source of income for farmers [27], and potentially reducing GHG emissions in energy applications [6,31].

Despite its attractiveness as an energy feedstock, there is still a need to assess the environmental impacts of SRW across different geographies to understand potential environmental trade-offs with other energy feedstocks. Life cycle assessment (LCA) is a method for quantifying the resource use and emissions to the environment across the full supply chain of products and processes, from raw material extraction through processing, distribution, use, and end-of-life [32,33]. This method allows for the identification of environmental hot-spots in the supply chain, the comparison of environmental impacts for alternative products and technologies, and modeling of alternative production scenarios. The LCA method has been used extensively to quantify the life cycle impacts and benefits of a range of wood-based bioenergy systems [14,34–38]. In particular, several LCA studies have revealed environmental and energy benefits and impacts of willow biomass production [31,39] and of various willow utilization pathways, such as electricity generation, direct combustion, combined heat and power, or bioethanol [40–49]. The earliest use of LCA to study the impacts of SRW was based on a US plantation [31]. Studies that followed have used parameters and chemical composition data for SRW feedstocks from previously published studies instead of using measured data that reflect actual feedstock characteristics for a given region.

In a review of 26 studies, Djomo et al. [50] highlighted the large range of energy balances and GHG emissions of bioenergy production from poplar and willow, which depend on yield and management practices (e.g. types and amount of fertilizer used and harvesting methods), and conversion technologies. It is important to quantify these differences for a range of feedstocks and technologies, across a range of geographic and climatic conditions, so that there is a stronger understanding of how bioenergy feedstocks can become more sustainable.

Therefore, the objective of this study was to evaluate environmental and energy impacts associated with generating 1 MJ of thermal energy from direct combustion of short rotation willow (SRW) pellets produced in Canada for 2 purposes: to determine where improvements could be made in the life cycle of SRW bioenergy to reduce impacts, and to compare SRW bioenergy to fossil fuel (light fuel oil and natural gas) for thermal energy. The study uses primary data from a SRW plantation at a research site at the University of Guelph, Ontario, Canada, the largest experimental willow establishment in eastern Canada. This study includes site-specific SRW characteristics and carbon sequestration modeling, and provides an assessment of additional environmental impacts and benefits beyond GHGs and energy balance, which is missing from many other studies [50]. Although this study is based on a case study in Canada, the findings and insights are relevant for other types of short-rotation crops in regions with similar climate and operating conditions, and also provide a better understanding of the geographical and management influences on biomass and bioenergy. The results can be used to support SRW cultivation activities and to understand the barriers and opportunities for sustainable expansion of SRW biomass production in other regions.

2. Methodology

We used the life cycle assessment methodology as described by the ISO 14040 [51] and 14044 [52] guidelines to conduct a comparative LCA for thermal energy generation from SRW biomass and conventional fossil fuels. The scope of the study is from cradle-to-grave, beginning with resource extraction and ending with heat generation and associated emissions in an industrial furnace.

2.1. Goal and scope

Our objectives were to: (1) identify environmental hot-spots in the SRW bioenergy life cycle to suggest improvements to the system, and (2) compare the life cycle impacts of producing thermal energy with SRW biomass and conventional fossil fuels. The main function of the system is to generate heat, therefore the functional unit for analysis of the bioenergy pathway is defined as the production of 1 MJ of thermal energy using average combustion technologies with 75% efficiency.

The system boundaries and process flow diagram for this study include the following major processes in the supply chain: production of material and energy inputs, SRW biomass production, pelletization, feedstock transportation, and combustion of pellets in