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Climate impact and energy efficiency from electricity generation through anaerobic digestion or direct combustion of short rotation coppice willow

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HIGHLIGHTS

- Using LCA, CHP from willow use in biogas was compared with direct combustion.
- Direct combustion was ninefold more energy-efficient.
- Biogas had a much greater cooling effect on global mean surface temperature.
- The effects of soil carbon changes on temperature over time differed.
- Biogas had long-term temperature effects, direct combustion short-term effects.

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ABSTRACT

Short rotation coppice willow is an energy crop used in Sweden to produce electricity and heat in combined heat and power plants. Recent laboratory-scale experiments have shown that SRC willow can also be used for biogas production in anaerobic digestion processes.

Here, life cycle assessment is used to compare the climate impact and energy efficiency of electricity and heat generated by these measures. All energy inputs and greenhouse gas emissions, including soil organic carbon fluxes were included in the life cycle assessment. The climate impact was determined using time-dependent life cycle assessment methodology.

Both systems showed a positive net energy balance, but the direct combustion system delivered ninefold more energy than the biogas system. Both systems had a cooling effect on the global mean surface temperature change. The cooling impact per hectare from the biogas system was ninefold higher due to the carbon returned to soil with the digestate.

Compensating the lower energy production of the biogas system with external energy sources had a large impact on the result, effectively determining whether the biogas scenario had a net warming or cooling contribution to the global mean temperature change per kWh of electricity. In all cases, the contribution to global warming was lowered by the inclusion of willow in the energy system. The use of time-dependent climate impact methodology shows that extended use of short rotation coppice willow can contribute to counteract global warming.

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1. Introduction

In order to decrease the climate impact from the European power sector, it is important to increase the share of renewable sources in the European power supply. Bioenergy is an important resource in the Swedish energy system making up 40% of the energy input in 2011 [1]. Bioenergy is frequently used in combined heat and power (CHP) applications, for which the Swedish forest industry is the largest supplier of biomass. In this study the effects on climate impact from heat and power generation using biomass from the agricultural sector were studied.

Short rotation coppice (SRC) willow is a well-established woody energy crop that has received particular attention over the last 30 years for its high potential dry matter (DM) yield and suitability for use in conventional CHP plants. It is often used for co-firing with other feedstock in large- or medium-scale CHP plants.

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Nomenclature

CHP	combined heat and power
SRC	short rotation coppice
DM	dry matter
C	carbon
SOC	soil organic carbon
GHG	greenhouse gas
LCA	life cycle assessment
GWP	global warming potential
CO_2	carbon dioxide
CH_4	methane
N_2O	nitrous oxide
ΔT_S	global mean temperature change
VS	volatile solids
LHV	lower heating value
HHV	higher heating value
OLR	organic loading rate
HRT	hydraulic retention time
ER	energy ratio
MC	moisture content
ICBM	introductory carbon balance model
iLUC	indirect land use change

An alternative way of generating electricity and heat is through gas engines. For instance, the majority of the biogas produced in Germany is used in small-scale CHP units that feed into the electricity grid. Farm-scale biogas is still a marginal bioenergy producer in Sweden [2]. It does however have a large potential, especially if manure and energy crops are used as feedstock for the digestion process [3]. Digesting manure alone in an anaerobic digestion process is expensive due to its high water content which lowers the effective output per unit volume of the digester. One way of increasing the output of the digester is to increase the DM and carbon (C) content of the substrate by co-digestion with a drier substrate [4].

Converting biomass to biogas enables the recycling of nutrients and C back to the field with the digestate, which can affect the soil organic carbon (SOC) levels [5,6], and, ultimately, the climate impact of the electricity generated. To our knowledge, no studies have been published quantifying how large this impact on the climate might be relative to those from the other parts of the bioenergy production system and how it may vary over time.

When evaluating the climate impact of electricity generated from biomass, one has to consider both greenhouse gas (GHG) emissions and the energy efficiency of the system used to generate the electricity. Life cycle assessment (LCA) methodology [7,8] is commonly used to achieve this. Several authors have investigated the energy efficiency and greenhouse gas emissions from electricity generating systems using SRC willow as feedstock [9–16]. Energy production from other SRC crops, such as poplar [17] and eucalyptus [18], have also been studied from a life cycle perspective. These can be cropped similar to SRC willow and often show similar energy and GHG performances [19,18]. Several studies have considered SOC changes when estimating the climate impact from SRC systems [11,20,13,14,16,21]. We are however not aware of any published LCA studies investigating the importance of timing of emissions in SRC willow systems and the effects of the digestate on SOC changes.

The most common way of characterizing the climate impact in LCA is to determine the global warming potential (GWP) [22]. However, this metric has been criticized, among other things, for not being able to capture the climate effects of C stock changes in biomass used for bioenergy when the life cycle net C balance is zero [23,24]. When a land use change occurs, the impacts on climate may also change over time due to SOC dynamics [25,26]. The inclusion of soil carbon changes and timing of GHG emissions in bioenergy LCA's of electricity and heat generation has been argued for in order to avoid false assumptions about the long and short term climate impact [27]. To capture and interpret these dynamic effects in an LCA is a challenge that requires a different impact indicator [28]. One such indicator is the global mean surface temperature change (ΔT_S) [29,16], which was used in this study.

The aim of this study was to compare the energy efficiency and climate impact of two ways of generating electricity and heat from SRC willow. The two energy conversion pathways investigated were (1) direct combustion in a central CHP plant and (2) conversion of the willow feedstock to biogas through co-digestion with liquid manure before burning the biogas in a small scale gas engine CHP. A trade-off between energy production and carbon sequestration similar to that of biochar systems [30] was expected. This paper serves the dual purpose of quantifying the time-dependent climate impact of different bioenergy systems as well as studying the trade-off between energy generation and climate impact mitigation through carbon sequestration that can be expected in the biogas scenario as digestate is added to the soil.

2. Methodology

Life cycle assessment methodology was used to assess the climate impact and effect on the energy efficiency from all relevant GHG and energy flows taking place throughout all life cycle stages of electricity and heat generation [7,8]. The study took the form of a comparative LCA with a cradle-to-gate perspective, starting with the extraction of resources and ending with delivery of the electricity generated to the grid. The timing of GHG fluxes was determined to assess the time-dependent climate impact [16] (see Section 2.7).

A model of a bioenergy production system using willow established on fallow land was set up. A dairy farm with 300 cows and with existing infrastructure for anaerobic digestion of the liquid manure and generation of electricity and heat from the biogas was assumed. Emissions and energy requirements related to construction and decommissioning of the infrastructure was excluded from the LCA for both scenarios.

In the biogas scenario, the willow was used within the current infrastructure on the farm, i.e. the willow biomass was co-digested with manure in the anaerobic digester and the biogas was combusted in a gas engine to generate electricity and heat (Fig. 1). In the direct combustion scenario the willow biomass was transported to a central CHP plant and incinerated in a furnace to generate electricity and heat. In both scenarios the electricity generated was fed into the Swedish electricity grid and the recoverable heat was delivered to local DH distribution systems.

2.1. System boundaries and general assumptions

The production of inputs, cultivation and harvest of willow, storage losses, transportation of biomass to the conversion facility, preparation of the biomass to be converted and return of the residues to the field were all included within the system boundaries (Fig. 1). Activities and losses taking place after the delivery of the electricity and heat, such as distribution losses, were outside of

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