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Determining the most sustainable lignocellulosic bioenergy system following a case study approach

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ABSTRACT

The paradigm shift from fossil to renewable energy sources is driven, largely, by a growing sustainability awareness, necessitating more sophisticated measurements in terms of a wider range of criteria. Technical efficiency, financial profitability, environmental friendliness and social acceptance are some of the aspects determining the sustainability of renewable energy systems. The resulting complexity and sometimes conflicting nature of these criteria constitute major barriers to the implementation of renewable energy projects.

The Worcester biomass procurement area in the Western Cape Province, South Africa, is used as a case study. It provides a blueprint for measuring the impacts of lignocellulosic bioelectricity systems – using life-cycle assessment (LCA), multi-period budgeting (MPB), geographic information systems (GIS) and multi-criteria decision-making analysis (MCDA), among others – and for prioritising the relevant criteria to determine the most sustainable technological option.

Following the LCA approach, 37 plausible lignocellulosic bioenergy systems were assessed against five financial-economic, three socio-economic and five environmental criteria. On translating the quantitative performance data into a standardised 'common language' of relative performance, an expert group attached weights to the considered criteria, using the analytical hierarchy process (AHP). Assuming the prerequisite of financial-economic viability, the preferred option comprises a feller-buncher for harvesting, a forwarder for biomass extraction, mobile comminution at the roadside, secondary transport in truck-container-trailer combinations and an integrated gasification system for the conversion into electricity. This approach illustrates how to internalise externalities as typical market failures, aiding decision makers to choose the most sustainable bioenergy system.

1. Introduction

The promotion of renewable energy sources is the result of a myriad of social, political and economic challenges. These include, amongst others, the need for security and diversification of energy supplies as well as for less reliance on fossil fuels, the uncertainty surrounding oil prices, and increasing concerns over environmental degradation and climate change effects [1].

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This new energy paradigm demands new ways of measuring the viability of energy sources. While in the past, the 'success' of energy carriers was mostly driven by financial considerations, leading to fossil fuels such as coal and oil being the preferred choices, the introduction of renewable energies has resulted in more of a sustainability driven approach, necessitating sophisticated measurements of a wide range of criteria. While financial-economic competitiveness still plays an important role, other medium- and long-term aspects need to be taken into account when considering the growing scarcity of fossil energy carriers. A major feature to any renewable product is the degree to which it can reduce environmental impacts, e.g. carbon dioxide (CO_2) emissions, associated with the use of fossil energy that it will replace. Another important feature, especially in developing and emerging countries, is the extent to which renewable energies can contribute to the socio-economic potential. Bioenergy particularly is considered a local energy source, as it requires large areas to ensure sufficient supply, resulting not only in a change of agricultural and forestry production patterns but also in significant employment creation, particularly in rural areas. In contrast, generating fossil-fuel-driven energy is considered a large-scale, capital-intensive operation, that is limited to relatively small areas, resulting not only in significant environmental impacts locally (e.g. acidification, eutrophication, human health) and globally (e.g. climate change), but also in other social challenges such as limited employment creation, migration to cities or infrastructure constraints.

Biomass is considered one of the most promising alternatives to conventional fuels and feedstocks, as it is the only renewable source of fixed carbon that can be converted to liquid, solid and gaseous fuels, heat and power [2]. Furthermore, the sequestration of carbon during biomass growth and the subsequent release of the carbon during the combustion process as CO2 can be considered a carbon neutral aspect of the bioenergy system. By contrast, fossil fuels release CO_2 that has been locked up for millions of years. Bioenergy has an almost closed CO_2 cycle, yet there are greenhouse gas emissions in its life cycle, resulting from its production: external fossil fuel inputs are required to produce and harvest the feedstocks, to process and handle the biomass, to operate bioenergy plants, and to transport the feedstocks and biofuels [3].

A variety of studies integrating LCA into a decision-making process concur that environmental, financial, and socio-economic criteria need to be considered when seeking the most sustainable alternative [4–6]. However, most of them fall short in their application, as they consider either only a single dimension (finance, social or environment) or take a limited number of other aspects into account [4–10]. This narrow measurement of 'success' may prevent implementation of the most sustainable alternative. Sustainability of production – referring to technical efficiency, economical affordability, environmental soundness, and socially acceptability [1] – is essential in the context of bioenergy projects, which depend on the support of stakeholders with different perspectives. This complexity constitutes a barrier to implementing renewable projects: information of a complex and conflicting nature, reflecting different viewpoints and changing with time, needs to be processed.

The Cape Winelands District Municipality (CWDM) in the Western Cape Province, South Africa, faces such a decision-making problem: An outdated electricity infrastructure and low capacities of electricity generated have resulted in scheduled power cuts by the monopolistically acting national energy supplier, ESKOM, which has had a severe impact on South Africa's economic growth. This prompted the public decision makers of the CWDM to investigate implementing local renewable bioenergy systems, aimed at improving energy security and reducing its dependency on ESKOM, while maximising sustainability. This necessitated identifying and evaluating potential bioenergy alternatives in terms of a variety of criteria.

1.1. *Cape Winelands district municipality*

The CWDM, with a total area of 2.23 million hectares (ha), is one of five district municipalities in the Western Cape. In 2010 its population was 679,210, with a labour force of 290,113 [11]. Of this, 230,196 people were employed, 202,782 workers are in the formal sector, and 27,414 workers are in the informal sector. In 2010, unemployment was estimated at 20.7%. The CWDM's climate is Mediterranean, and it has a historically strong deterministic water supply (winter rainfall) from April to August.

A previous study by the authors assessed the land availability and resource productivity in the CWDM [12]. Non-suitable areas, such as urban areas, areas with terrain limitations (i.e. areas that are too steep: >35%), areas with water limitations (aridity index) and ecologically sensitive areas (e.g. protected areas, critical biodiversity areas, and water catchment areas), as well as intensively and extensively used agricultural and forestry land were excluded *a priori*, leaving about 175,000 ha (ha) for producing energy wood in SRC systems.

In order to ensure food production, which is considered particularly important in a South African context, the study was limited to biomass production in short-rotation coppice (SRC) systems. The productivity assessment indicated that about 1.4 million tonnes of fresh lignocellulosic biomass could be supplied annually, assuming medium productivity [12]. Eighteen tree species were identified as being suitable for the area and climate conditions, of which four are indigenous and 14 exotic. Compared to exotic species, indigenous species (e.g. *Acacia karoo*) are expected to produce higher yields in the interior, low production-potential areas in the north-east of the CWDM, whereas exotic species (e.g. *Eucalyptus cladocalyx*) grow better in areas with higher production potential.

Fig. 1 shows potential areas in the CWDM for producing woody biomass and for bioenergy conversion. Fourteen potential conversion sites were identified [13] based on their proximity to substations and major grid lines, to minimise feed-in costs; proximity to potential purchasers of thermal energy, resulting in improved profitability; and demand for electricity from towns. The proximity of the demand points to the road network was another consideration, as this affects transport efficiency and obviates the costs of additional infrastructure.

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