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Research paper

Current and future technical, economic and environmental feasibility of maize and wheat residues supply for biomass energy application: Illustrated for South Africa

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ABSTRACT

This study assessed the feasibility of mobilising maize and wheat residues for large-scale bioenergy applications in South Africa by establishing sustainable residue removal rates and cost of supply based on different production regions. A key objective was to refine the methodology for estimating crop residue harvesting for bioenergy use, while maintaining soil productivity and avoiding displacement of competing residue uses. At current conditions, the sustainable bioenergy potential from maize and wheat residues was estimated to be about 104 PJ. There is potential to increase the amount of crop residues to 238 PJ through measures such as no till cultivation and adopting improved cropping systems. These estimates were based on minimum residues requirements of 2 t ha^{-1} for soil erosion control and additional residue amounts to maintain 2% SOC level.

At the farm gate, crop residues cost between 0.9 and 1.7 \$ GJ^{-1}. About 96% of these residues are available below 1.5 \$ GJ^{-1}. In the improved scenario, up to 85% of the biomass is below 1.3 \$ GJ^{-1}. For biomass deliveries at the conversion plant, about 36% is below 5 \$ GJ^{-1} while in the optimised scenario, about 87% is delivered below 5\$ GJ^{-1}. Co-firing residues with coal results in lower cost of electricity compared to other renewables and significant GHG (CO_2 eq) emissions reduction (up to 0.72 tons MWh^{-1}). Establishing sustainable crop residue supply systems in South Africa could start by utilising the existing agricultural infrastructure to secure supply and develop a functional market. It would then be necessary to incentivise improvements across the value chain.

1. Introduction

Utilisation of agricultural residues for large scale modern bioenergy production is now a common practice in many countries [1–3]. Several countries such as Denmark, UK, Spain, Sweden, China and India have developed large scale crop residue energy facilities [2,4,5]. Key crop residues include maize stover, wheat straw, rice straw and husks and bagasse [6–8]. Globally, the use of sugarcane bagasse for power and heat production is the most common and mature energy application of crop residues for those countries with large sugarcane industries [3]. There is less experience in energy conversion for other crop residues, but interest is

Abbreviations: Business As Usual or Base Case (scenario), BAU; Emerging economies of Brazil, Russia, India, Indonesia, China and South Africa, BRIICS; Carbon, C; Central gathering point, CGP; Carbon Dioxide, CO_2; Coal-biomass to power, CBtP; Coal-to-power, CtP; European Commission, EC; Food and Agriculture Organisation of the United Nations, FAO; Greenhouse gas, GHG; International Energy Agency, IEA; Integrated Model to Assess the Global Environment, IMAGE; Intergovernmental Panel on Climate Change, IPCC; Life-cycle analysis, LCA; Local distribution centre, LDC; Nitrogen, N; Nitrous oxide, N_2O; Ammonia, NH_3; Nitrogen oxides, NO_x; Operation and maintenance, O&M; Organisation for Economic Cooperation and Development, OECD; Residue to product ratio, RPR; Soil organic carbon, SOC; Soil organic matter, SOM; Torrefied pellets, TOPs.

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significant in using maize stover for advanced biofuels, especially in the United States [6,9,10]. In Europe, Denmark pioneered large scale power generation using straw and has commercialised the technology since 1989 [1,11]. A key advantage of using crop residues is that their use leads to minimal to no land use change impacts (compared to energy crops).

According to the Intergovernmental Panel on Climate Change (IPCC) biomass energy deployment scenarios [6], agricultural residues are likely to play an important role in future energy systems contributing between 15 and 70 EJ to long term global energy supply. Agricultural residues are considered to be less contentious, low cost, carry few risks [6,12,13] and thus represent an important energy resource for countries with a large agricultural production base.

There is limited literature offering a comprehensive methodology for assessing the crop residue harvesting and supply, while taking into account sustainability criteria (key being maintenance of soil fertility, nutrient and carbon levels as well as avoiding displacement of other competing uses of residues). Available studies on crop residue potentials present widely varying results, which is largely due to poor understanding of factors that determine the potential availability and results in simple assumptions being used for quantifying these factors. Good examples of international studies that evaluate sustainable crop residue removal include Junginger et al. [14], Gallagher et al. [15], Nelson et al. [16], Andrews [17], Cosic et al. [18] and Daioglou et al. [19]. Most studies only evaluate part of the supply chain or exclude the economic feasibility. Cosic et al. [18] apply a methodology for economic bioenergy potential of various crop residues in Croatian counties, taking into account critical sustainability criteria and including supply chain economics up to the final conversion facility. Such assessments are useful for identifying what can sustainably be mobilized from the farm, but also what is economically feasible for bioenergy applications.

For countries such as South Africa, where the understanding of crop residues production and supply potential is limited, it is imperative that assessments be conducted to evaluate the technical, economic and environmental feasibility of their utilisation. South Africa was selected as a case study because it is a large country with a large agricultural production base where significant amounts of biomass are potentially available for energy purposes [20]. In addition, crop residue use and soil erosion control are critical issues given South Africa's semi-arid climate and geographic diversity. Only a few studies have been conducted on the bioenergy potential of agricultural residues for South Africa. Examples include Cooper and Laing [21], OECD/IEA [22], Euler [23], Potgieter [20] and Valk [24]. There have been no recent published assessments apart from the Bioenergy Atlas referred to in Hugo [25] and other more general and descriptive studies such as Etambakonga [26] and Petrie [27]. Green Cape [28] focuses more on fruit industry waste in Western Cape province. Cooper and Laing [21] provide very crude theoretical crop residue potentials in South Africa and do not take into account any sustainability criteria. The International Energy Agency (IEA) study [22] provides some crude estimates of crop residue potentials based on national crop production statistics, and it also estimates residue supply costs. Potgieter [20] assesses the maize and wheat residue potential in the Greater Gariep agricultural area (Northern Cape). This study is limited in geographical scope and uses Google Earth satellite imagery to estimate biomass production areas. It also employs simplified biomass removal assumptions (e.g. that 75% of biomass is recoverable). Euler [23] estimates detailed bioenergy potentials from various sources including agricultural residues. This study also provides insights into the supply chain economics to a centralised national conversion facility. However, Euler [23] does not account for soil organic carbon demands and does not perform detailed competing biomass application analysis. Valk [24] provides a more detailed analysis of sustainable potential of biomass from crop residues in South Africa, taking into account state-of-the-art methodology and key factors. Despite applying a detailed methodology, the spatial resolution in this study is not detailed for both the residue availability and cost supply analysis.

According to DOE [29], South Africa is also developing a Bioenergy Atlas which will provide comprehensive data and thorough analysis of availability and potential of the country's bioenergy resource. However, the contents of the Atlas have not been made public yet. South Africa is also developing a Biomass Action Plan for Electricity Production (BAPEPSA) co-funded by the Dutch government and the electricity utility, Eskom [29].

Current studies also have not attempted to develop cost supply chains at the district level resolution or assess the impact of optimising the supply chain. This study, on the other hand, assesses the main biophysical factors and competing uses that determine the residue availability for energy purposes in order to determine the theoretical and sustainable potential for energy generation from agricultural residues in a case study for South Africa. In addition, the study analyses biomass availability at a detailed spatial scale to capture the unique local settings of the various districts such as crop yields, soil types, rainfall, temperature, livestock and transport characteristics. It also provides cost supply curves for the biomass supply from all potential locations to a centralised conversion location in Mpumalanga province.

Objectives

This study assesses the technical, economic and environmental feasibility of mobilising crop residues for large scale biomass energy applications in South Africa. The study focusses on two main crop residues, maize stover and wheat straw, since these two crops represent the largest crop production volumes in the country and therefore potentially have the largest residue potential in South Africa [20,23,24]. It assesses the residue potential from commercial agricultural production only since potential from subsistence agriculture is assumed to be low given the typically low yields [30,31], and thus most of residues produced should be left in the field for soil conservation purposes.

A key objective of this study is to estimate quantities of maize and wheat crop residues that can be removed for bioenergy use from farming areas, while maintaining soil productivity and health, and also maintaining rain and wind erosion rates at tolerable soil-loss levels. These quantities represent the so-called sustainable residue removal rate which is the key environmental constraint that limits the use of crop residue for energy. In addition, the study also evaluates the environmental impact of the production and supply of crop residues using greenhouse gas emissions and associated carbon abatement costs as key criteria.

In addition, the study also aims to determine the cost of crop residues at the farm gate and at the factory gate for both dryland and irrigation type farming. At every stage of the supply chain, the study identifies optimisation measures that would improve the performance of the overall crop residue supply chain and enhance the competitiveness of biomass with respect to conventional fuels.

This article is structured as follows. Section 2 outlines the study methodology while section 3 and 4 summarises the results. Section 5 discusses the uncertainties in the analysis while section 6 presents the necessary preconditions required to secure and mobilise large volumes of agricultural residues. All energy values given in this study are in higher heating value (HHV) terms and represent annual energy flows. All biomass weight values are in dry tonnes unless stated otherwise.