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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

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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.

2. Approach and methodology

The general approach used in assessing the feasibility of mobilising agricultural residues for large scale energy conversion follows six stages which are outlined briefly below. This procedure is discussed in detail in Junginger et al. [14]:

a. The first step estimates the theoretical crop residues production potential based on the agricultural production levels (at the required spatial scale) and the residue production ratios (RPR). In addition, the physical and chemical characteristics of the residues are determined (e.g. moisture content, calorific values).
b. Second, various sustainability criteria and other constraints that limit residues availability are identified considering existing conditions in the country and international best practice. Environmental constraints are imposed to protect soil against erosion and to maintain soil organic carbon (SOC). Other aspects taken into account include agricultural management practices such as tillage practices, harvesting methods, residue recovery (equipment) constraints and infrastructure availability.
c. The third step determines unutilised residues by taking into account residues that are used in competing applications (e.g. feed, fuel, fertiliser, fibre). Step two and three employ the methodology developed by Valk [24] and described in Section 2.1.3.
d. Step four determines the net available biomass residues potential after taking into account supply constraints and deducting competing applications.
e. Step five evaluates the logistical requirements for supply of residues from the farm to the final conversion plant. At this stage also the harvesting, collecting and pre-treatment technologies and associated costs are evaluated. In addition, transportation and storage requirements are evaluated to estimate the delivered cost per tonne of biomass. The methodology for evaluating the logistics of the crop residue fuel chain is based on Batidzirai et al. [32].
f. The last step is the composition of biomass supply curves based on various scenarios (which are determined by the parameters in the previous steps) and show the variation in available biomass at different cost levels. The methodology for developing the logistics of the supply curves is adopted from van der Hilst and Faaij [33]. Estimates are also made of the final conversion costs and this is used to compare final energy production costs and GHG impacts with other electricity supply technologies.

2.1. Methodology for estimating sustainable crop residue potential

2.1.1. The function of residues in agricultural production systems

Residues play a vital role in sustaining agricultural production systems, through mainly soil erosion control and soil conditioning [17,34–39]. These functions therefore represent direct competing applications of crop residues and have to be accounted for when estimating sustainable crop residue potentials.

Residues requirements for soil erosion control: A residue cover protects the soil from water and wind erosion [40–42]. From literature, residue cover requirements for soil protection range from 13% [43,44] to 80% [45] and the assumptions vary widely [40]. For example, Gallagher et al. [15] and Busaria et al. [46] assume a 30% required soil cover, while Kim and Dale [47] argue that 60% residue cover is necessary to allow for uncertainties about the local conditions. Cosic et al. [18] assume that 1–2 t ha^{-1} of wheat straw soil cover is required while for maize stover, 20–30% of stover is adequate for erosion control. Papendick and Moldenhauer [48] and Andrews [17] have shown that soil loss is reduced to 10% by a residue cover of about 45% and 70% for wind and water erosion respectively compared to 100% residue removal. A residue cover of 70% would require roughly 2 t ha^{-1} of residues. Andrews [17] observed that leaving more than 2 t ha^{-1} of residues only has a very limited effect in reducing soil loss under no-till conditions, as shown on Fig. 1 [17].

Residues requirements for maintaining SOM and soil nutrients: Residues (both above and below ground) are essential for recycling valuable nutrients and maintaining soil organic matter (SOM), improving microbial activity and soil quality [37]. SOM loss is mainly caused by long term cultivation of land and soil erosion

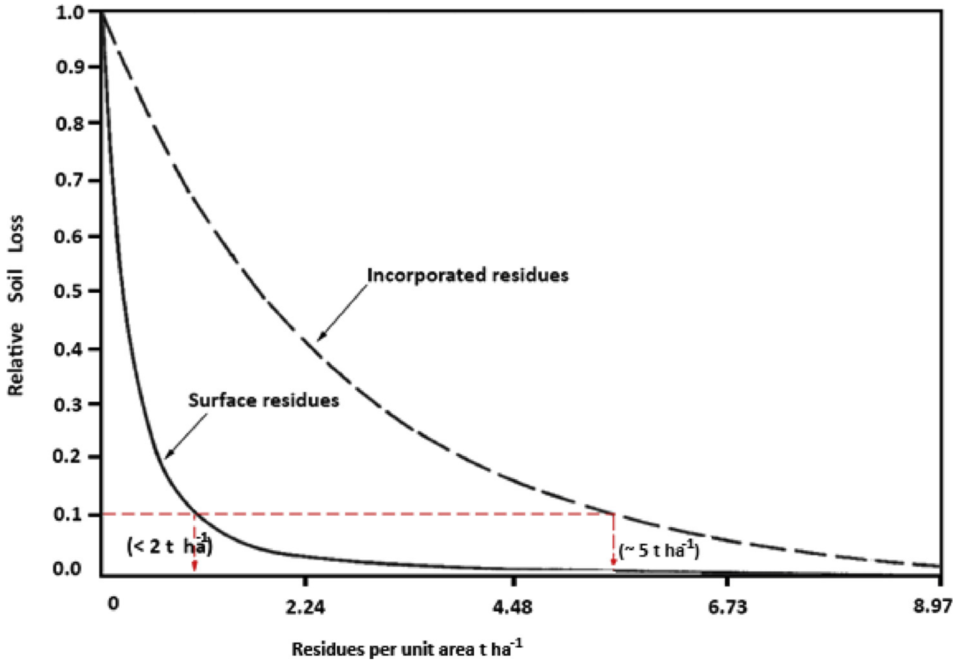


Fig. 1. The difference in soil erosion protection between surface residues and incorporated residues.
Source: Adapted from Papendick and Moldenhauer [48] and Andrews [17].

[34,49–51]. Residues also improve soil physical properties such as soil tilth and water infiltration [46]. In addition, a residue cover assists in soil water conservation and reducing soil temperature fluctuations, which is important in semi-arid conditions [39,52–56].

This SOM is derived from above ground residues, below ground residues and rhizodeposition (root exudates and other root borne organic substances released during root growth). Below ground residues and rhizodeposition are important contributors to SOM [34,57]. The relative contribution of below ground residues to SOM is greater than that of above ground residues since the carbon is more efficiently converted into soil organic carbon (SOC) [34]. Only 11–13% of carbon in above ground residues is incorporated into SOC compared to 37–50% for below ground biomass [58]. The difference is attributed to the slower decomposition of roots due to the high lignin content and lesser soluble carbon [34,59]. For sustainable agriculture, Brady and Weil [60] argued that a SOC of 3% is ideal for agricultural soils, while Stronkhorst and Venter [61] argue that a SOC between 1 and 3% is required. On the other hand Lal [62] contends that 1% SOC is the critical level for crop production. Based on these studies, this study therefore uses an average 2% SOC level in 20 cm topsoil, as recommended by Valk [24]. Although a 3% SOC level is considered ideal for sustainable agriculture, this is not realistic for all soils in South Africa [63]. As a result, in South Africa, residue requirements range from 4.1 to 5.8 t ha^{-1} for maize stover, and 4.6–7 t ha^{-1} for wheat straw [24]. These differences arise from regional variations in the soil clay content and climatic conditions.

Apart from improving soil quality, SOM also acts as a reservoir of nutrients that can be gradually released into the soil. Organic matter retains nutrients and prevents them from leaching to deeper soil layers [56,64]. Available nutrients that are not taken up by plants are retained by soil organisms [52–55]. Thus, SOM plays an important role in maintaining soil fertility also in addition to other functions [40]. However, to ensure that soil productivity is maintained when crop residues are partially removed, the amount of nutrients embodied in the residues has to be compensated by an equivalent amount of inorganic fertilisers. We factor this nutrient compensation as a cost element as explained in Section 2.2.

Residue demands by competing uses: The most important application of crop residues in South Africa is for livestock [20]. Wheat and maize residues are commonly used for livestock bedding and feed during winter when forage is poor and livestock is kept indoors [18]. For maize stover, the cattle feed demand depends on the cattle herd in a particular area and the length of the grazing season [15]. It is assumed that maize stover constitute only 25% of the dry matter feed requirement [65,66]. Wheat residues are primarily used as animal bedding since the feed value is low [67,68]. This study only considers cattle, pigs and sheep as they are the largest consumers of wheat straw. The average duration of this livestock wintering activity is about 70 days, limited by the window between harvest and field preparation for the coming crop production season [69].

2.1.2. *Factors affecting crop residue availability*

Removal of agricultural residues is directly influenced by a number of factors including type of crops, crop yield, crop rotation, agricultural management practices (e.g., tillage), climate, and physical characteristics of the soil such as erodibility and topology, as given below:

- *Management practice*: Soil tillage is important for weed control, incorporation of residues, erosion control, improving soil structure and moisture control [37,39,70]. No-till cultivation combined with a residue cover generally results in less erosion than conventional tillage [17] as shown in Fig. 1. Also the amount and distribution of SOM changes with the tillage system [38,46]. Generally, no till cultivation increases SOC storage in the top 10 cm of soil [34,51,71] and thus results in less residue requirements to maintain a specific SOC level. On the other hand, conventional ploughing buries most residues and increases oxidation of organic matter. With no-till, residues are left on the soil surface where decomposition is slow, which then causes organic matter in the upper soil to increase after several years. Also crop roots decompose more slowly than aboveground residues, and so tend to contribute relatively more to soil organic matter than aboveground residues [71]. The presence of a cover crop also positively affects SOM [49].
- *Crop type and residue yield*: The amount of crop residues produced depends on the crop yield and the ratio of residue to grain (the so-called residue-to-product ratio, RPR). For high residue yielding crops such as maize, an increasing amount of residues can be removed since the amount of residues required to maintain soil productivity is not dependent on crop yield [7,72]. It is thus preferred to harvest high residue crops and in good yield years. Also crop residues with a high C:N ratio decompose slowly, and can thus allow greater accumulation of SOM [59,73].
- *Climate*: Residue harvest in warm and humid areas is high-risk as SOM decomposes much faster than in cooler drier areas [59]. SOM is therefore negatively affected by warm and moist conditions.
- *Soil type*: SOM levels can be maintained with less residues in fine-textured soils with restricted aeration [18,40]. Decomposition of organic matter occurs more slowly in poorly aerated soils, where oxygen is limiting or absent, compared with well-aerated soils. Thus heavy clay and poorly drained soils allow higher residue removal than coarser textured soils [40,59].
- *Topography*: Areas with steep slopes are more prone to runoff and soil erosion, and thus require greater amounts of residues [18,55].

2.1.3. *Estimating sustainable crop residue potential*

The gross amount of crop residues produced (or theoretical potential) in South Africa is estimated based on the national crop production, crop yields, residue-to-product ratios, area under cultivation, and moisture content. To estimate the sustainable crop residue that can be available for biomass energy purposes, the amount of residues required to prevent soil erosion and maintain soil carbon, as well as amount of residues required for competing applications are deducted from the gross residue potential. We use the methodology developed in Valk [24] as presented below:

(a) Estimating the theoretical crop residue potential

The theoretical potential is calculated according to Equation (1).

$$THP = Y \times RPR \times A(1 - MC) \times HHV_{dry} \quad (1)$$

Where:

THP is the theoretical potential of the residues (GJ),
Y the fresh matter (*fm*) yield of the main product in (t ha^{-1}),
RPR the residue-to-product ratio (t t^{-1}),
A the production area (ha),
MC the moisture content (%),
HHV_{dry} the higher heating value of the residues (GJ t^{-1}).

We assume as average HHV for maize stover and wheat straw of 18.2 and 17.8 GJ t^{-1}, respectively [74,75]. The moisture content of the crop residues is assumed to be 7% (in the range 5–9%) at baling

[76–78]. In this study we have assumed a simple residue-to-product ratio (RPR) of 1:1. This is however a simplistic assumption as several studies have shown that there is a relation between the RPR, the crop yield and various other factors [79].

(b) Estimating the Sustainable Crop Residue Potential (accounting for soil requirements)

The sustainable potential is calculated using Equations (2) and (3) below:

$$\text{If}\,(S\text{-}BGR) > E \text{ then}: SP = THP - \left((S - BGR) \times A \times HHV_{dry}\right) \tag{2}$$

$$\text{If}\,(S\text{-}BGR) < E \text{ then}: SP = THP - \left(E \times A \times HHV_{dry}\right) \tag{3}$$

Where *SP* is the sustainable potential of the harvest residues (GJ), *S* the total amount of residues (above- and belowground) required to maintain 2.0% SOC (t ha^{-1}), *BGR* the belowground residues (t ha^{-1}), *E* the amount of residues required to reduce erosion rates to 10% of the bare soil erosion (t ha^{-1}), *A* the area under cultivation (ha), HHV_{dry} the higher heating value (GJ t^{-1}).

For erosion control, we use 2 t ha^{-1} of residue cover as recommended by Andrews [17]. The required residue inputs to maintain a 2.0% SOC level for different climatic conditions and soil types are calculated with the Rothamsted organic carbon model ([80] for model; as applied in Ref. [24]), which models the decay of organic inputs into resistant plant material, humified organic matter and finally inert organic matter. This model takes into account climate conditions (monthly rainfall, temperature and evaporation), soil type (based on the clay content) and the months in which the soil is covered with a growing crop. The model has been validated on multiple occasions using test trials across a number of biomes [80–82].

(c) Estimating the sustainable crop residue potential (accounting for competing residue uses)

This study only accounts for the use of residues for animal feed and bedding.

The demand for maize stover as an animal feed: To account for residue uses for animal feed, the sustainable maize stover potential is determined using Equation (4):

$$SP_{net} = SP - (365 - GS) \times 0.25 \times CP \times FR \times HOC \times HHV_{stover} \tag{4}$$

Where SP_{net} is the net sustainable potential (GJ); *SP* is the sustainable potential −accounting for soil requirements (GJ); *GS* the duration of the grazing season (days); *CP* the part of the cattle population feeding on residues (%); *FR* the feed requirement of cattle, 12 kg on average [15] (t day^{-1}); *HOC* Heads of cattle; and HHV_{stover} the higher heating value of maize stover (GJ t^{-1}).

The demand for wheat straw as animal bedding: the potential for wheat straw is determined as follows:

$$SP_{net} = SP - ([365 - GS]*[HOC*LP*BRC*HOS*LP*BRS + HOP*LP*BRP])*HHV_{straw} \tag{5}$$

Where *HOC, HOS, HOP* the heads of cattle, sheep and pig, respectively; *LP* the livestock population using bedding (%); *BRC, BRS, BRP* the bedding requirement for cattle, sheep and pig, respectively (t day^{-1}); and HHV_{straw} the higher heating value of wheat straw (GJ t^{-1}).

2.2. Cost of biomass

Given the differences in crop yields and farming operations for production of maize and wheat using dryland and irrigation farming, the associated residue collection costs are also different. According to DAFF [67,68], crop yields are higher in irrigation farming (8 t ha^{-1} for maize and 5 t ha^{-1} for wheat) compared to dryland farming (3.5 t ha^{-1} for maize and 2 t ha^{-1} for wheat). It is assumed that the work rate in dryland farms using a large square baler can be about 120 ha d^{-1} while in irrigation farms only 90 ha d^{-1} can be covered [67,68]. This leads to disparities in the effective time of use of machinery, and consequently on residue collection costs. A distinction is therefore made for dryland and irrigation residue costs. Costs of residues at the farm gate are divided into direct and indirect costs. Direct costs include residue harvest operations and transport costs. Indirect costs are the compensation a farmer requires for the loss of nutrients due to residues harvesting. In addition, a farmer profit margin is included to the total costs, as an incentive to put in the extra work required to harvest the residues [83]. This profit margin is assumed to be 10% [84]. Total annual costs at farm gate (*CFG* in \$ t^{-1}) are calculated using Equation (5):

$$CFG = \left(\sum_i I_i + 0\&M_i\right) \times (1 + P) + NCC$$

Where:

I_i: Annualised investment cost for activity *i* (\$ t^{-1}).
$O\&M_i$: Operation and maintenance cost for activity *i* (\$ t^{-1}).
P: Overall profit margin for farmer (%).
NCC: Nutrient compensation costs (\$ t^{-1}).

2.2.1. Indirect costs- farmer compensation for lost nutrients

Agricultural residues contain a certain amount of vital nutrients, mainly nitrogen, potassium and phosphorous [15]. These nutrients are removed with the residue harvest. Since the farmer must make up for this nutrient loss by adding additional fertiliser in order to maintain yields, he must receive a financial compensation [17,83].

The nutrient compensation costs (*NCC* in \$ t^{-1}) are calculated according to Equation (6).

$$NCC = \sum_i NC_i \times F_i \tag{6}$$

Where:

NC_i: Nutrient content (t t^{-1})
FC_i: Fertiliser cost (\$ t^{-1}).

This assumes similar nutrient uptake efficiencies by plants for both fertiliser and crop residues. Table 1 shows the (breakdown of) the nutrient compensation cost for maize stover and wheat straw. These nutrients levels are presented on an N, P_2O_5, K_2O basis.

2.3. Supply chain analysis

Strategies for supplying crop residues from farming areas around the country to the conversion plants are primarily targeting minimising costs and environmental and other externalities, and maximising energy efficiency. We assume in this study that the crop residues are destined for co-firing in a typical power plant located in Mpumalanga province near Johannesburg (where most of the coal fired power plants are located). We take Camden power plant as an example. Camden is a 1600 MW, 46 year old coal fired power plant situated close to Ermelo in Mpumalanga [88].

2.3.1. *Supply chain design*

Fig. 2 shows the structure of the supply chain for delivering crop residues from the farm to the conversion plant. The actual required activities mainly depend on whether pre-treatment is required. From the farm, the residue are baled and transported to either an on-farm storage site or to the local distribution centre (LDC) being the nearest centre or town with logistical infrastructure to handle biomass from a particular region. From the LDC, biomass is transported to the conversion plant.

Organisation of crop residue supply chains from the various farming areas to the conversion plant requires optimal planning to ensure cost effective delivery at the plant gate. Loose crop residues are difficult to handle and bulk densities are low, making it difficult to transport and store them efficiently. These properties can be improved by pre-treating the residues early in the supply chain before transport to the conversion plant.

Two approaches are used in this study to analyse the supply of crop residues, based on (i) least cost national supply strategy and (ii) distance cumulative availability. For the first approach, we identify crop residue availability across the country and their spatial distribution. After determining the farm gate costs for the crop residues, supply chain costs to the conversion plant are estimated; and a national cost supply curve is derived.

The second approach attempts to identify biomass resources that are closest to the conversion plant and therefore logistically easier to procure. To accomplish this, the South African map is used to plot the biomass resources as in the first method. Available biomass is then mapped into radial circles based on distance from the conversion plant. The relative supply chain costs to the conversion plant are then estimated for each successive 50 km radial circle to build a distance-cumulative supply curve.

2.4. *Greenhouse gas emissions (GHG) and comparison of GHG mitigation costs*

The methodology for estimating GHG emissions along the crop residue supply chain follows the European Commission (EC) guidelines [89] for calculating the GHG performance of biomass use in electricity, heating and cooling. The functional unit used in this study is the 'tonne (of CO_2 equivalent) per megawatt-hour of electricity produced' (t MWh^{-1}). Two cases are compared in this study: the reference case which is based on coal fired electricity production and the alternative scenarios based on co-firing crop residues with coal at a ratio of 30:70 on an energy basis. GHG emissions (CO_2 eq) for the reference case are based on emissions for a typical South African coal fired power plant (estimated to be about 0.99 t MWh^{-1}) [90,91].

2.4.1. *System boundaries and estimating GHG emissions*

Following EC guidelines [89], the system boundary for bioenergy production from crop residues is defined as shown in Fig. 3. Biomass feedstock from waste such as agricultural residues is considered to have zero life-cycle GHG emissions "up to the process of collection of those materials". Therefore the GHG emissions from the grain enterprise are excluded and at the farm, only the emissions associated with collecting/harvesting, baling and forwarding crop residues are included. However, since residue removal results in some soil nutrient losses, nutrient compensation by inorganic fertilisers is taken into account. Thus GHG emissions from the application of an equivalent amount of fertiliser are included in the overall GHG performance of the supply chain.

Six subsystems can be identified in Fig. 3: the grain enterprise, crop residue harvesting, first transport, pre-processing/densification, second transport and final conversion. Apart from GHG (CO_2 eq) emissions associated with nutrient compensation at the farm, GHG emissions (in t MWh^{-1}) from activities in the other five subsystems along the supply chain are calculated for the selected scenarios based on the energy use at each stage of the supply chain as given in Equation (7). The GHG emissions associated with construction of plant and equipment supply are not considered in this study.

$$GHG = E_{nc} + E_{hc} + E_{ft} + E_{p} + E_{st} + E_{fc} \tag{7}$$

Where:

E_{nc} – CO_2 eq emissions from inorganic fertiliser use in nutrient compensation (t MWh^{-1})
E_{hc} – CO_2 eq emissions from harvesting and collection of crop residues at the farm (t MWh^{-1})
E_{ft} – CO_2 eq emissions from first truck transport (t MWh^{-1})
E_{p} – CO_2 eq emissions from pre-processing and densification (t MWh^{-1})
E_{st} – CO_2 eq emissions from second transport by rail or truck (t MWh^{-1})
E_{fc} – CO_2 eq emissions from final conversion to electricity (t MWh^{-1}).

GHG emissions due to nutrient compensation of residue removal are calculated using the following equation:

Table 1
Nutrient compensation cost for the removal of maize and wheat residues.

	Nutrient	Nutrient content (kg t^{-1})[a]	Fertiliser cost (\$ t^{-1})[b]	Nutrient composition cost (\$ t^{-1})
		A	B	C = A*B
Maize stover	Nitrogen	7.18	566	4.06
	Potassium	1.28	799	10.23
	Phosphorus	2.13	680	145
	Total			15.74
Wheat straw[c]	Nitrogen	4.99E	566	2.83
	Potassium	9.07E	799	7.25
	Phosphorus	1.36E	680	0.92
	Total			11.00

Source:
[a] Milhollin et al. [85].
[b] Grain SA [86] – 5-year average fertiliser costs.
[c] Mullen [87] for nutrient content.

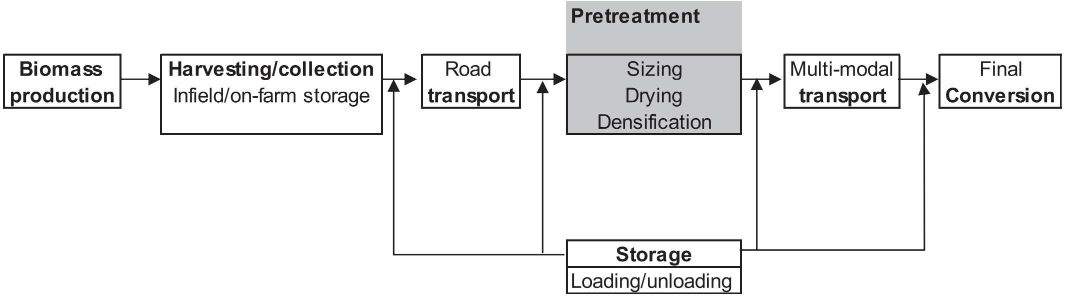


Fig. 2. Outline of biomass energy supply chain elements.

$$E_{nc} = \left[\sum_i \left(NC_i \times EF_{ft} \right) \times B_{in} + E_{N_2O} \right] \Big/ \left(B_{in} \times HHV/3.6 \right) \times \eta_{CBtP} \tag{8}$$

Where:

NC_i – the nutrient content of crop residue type i (t t^{-1})
EF_{ft} – the carbon footprint (CO_2 eq) of inorganic fertiliser production (t t^{-1})
B_{in} – the amount of input biomass residue feedstock utilised in power plant (t y^{-1})
E_{N2O} – N_2O emissions from application of inorganic fertilisers and crop residue on managed soil (t CO_2 eq). The methodology for calculating N_2O emissions is described below
η_{CBtP} – power conversion efficiency of co-firing coal and biomass in a coal-biomass to power (CBtP) plant (%).

The carbon footprint of inorganic fertilisers (from cradle to gate) is derived from Kool et al. [92] and given in Table 2. Global average values are used in this study since South African specific emission factors are not available. In addition, the South African fertiliser industry is heavily dependent on fertiliser imports from the global market [93].

Application of nitrogen-containing fertilisers to managed soils results in direct nitrous oxide (N_2O) emissions through microbial (de)-nitrification on site and indirect N_2O emissions following volatilization/re-deposition of NH_3 and NO_x and leaching of Nitrogen (N) [94,95] as shown in Equation (9). These GHG emissions (including default emission factors) are calculated based on the Tier 1 methodology following IPCC guidelines [96]:

$$N_2O = N_2O_{(Direct)} + N_2O_{(ATD)} + N_2O_{(L)} \tag{9}$$

Where:

N_2O – total N_2O emissions from fertiliser use on managed soils (t N_2O)
$N_2O_{(Direct)}$ – direct N_2O emissions from point of application of fertiliser (t N_2O)
$N_2O_{(ATD)}$ – indirect N_2O emissions from atmospheric deposition of volatised N (t N_2O)
$N_2O_{(L)}$ – indirect N_2O emission produced from leaching and run-off of N (t N_2O).

For direct emissions, we assume that nutrient compensation involves replacement of exact quantities of N from crop residues by the equivalent in synthetic fertilisers, this is a simplified assumption that the net N_2O emissions are zero and the same emission factor (0.01 t N_2O-N (t N)$^{-1}$) is used for both organic and inorganic fertilisers (this is a highly simplified supposition as it assumes that the N in crop residue decomposes completely into N_2O, but the decomposition is partial in reality and this needs further analysis

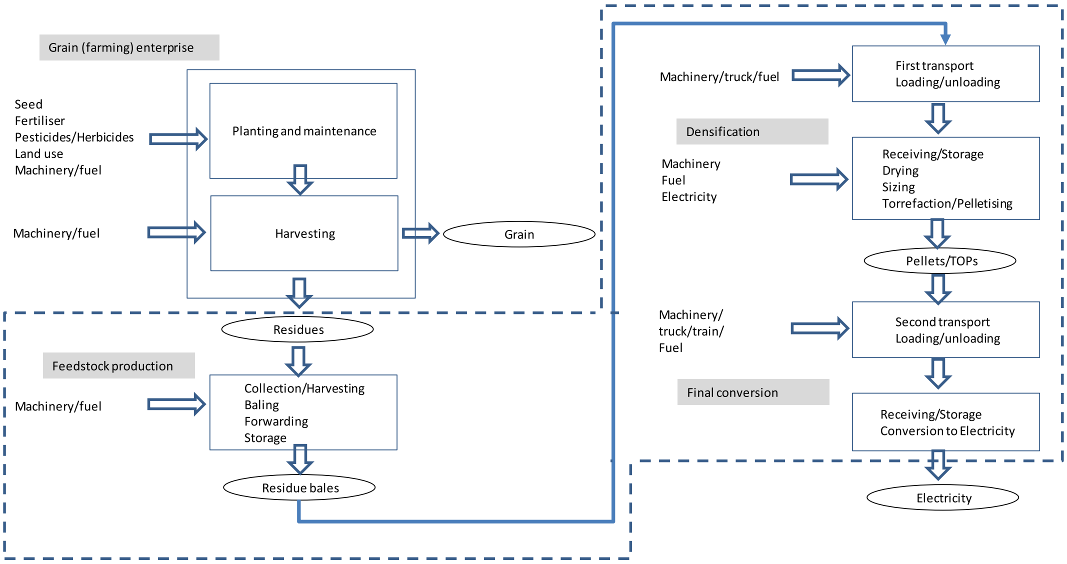


Fig. 3. System boundaries for GHG performance of crop residue based electricity production chain.

and can be subject of further research). Similarly, we also assume that there are zero net N_2O emissions from leaching and runoff of N. Therefore only N_2O emissions resulting from volatisation and redeposition of N are estimated as follows:

$$E_{N_2O} = NC_i \times Frac_{GASF} \times EF_{ATD} \times (44/28) \times GWP_{N_2O} \quad (10)$$

Where:

E_{N2O} – GHG emissions from $N_2O_{(ATD)}$ (t CO_2 eq)
$Frac_{GASF}$ – the fraction of synthetic N fertiliser that volatises as NH_3 and NO_x (0.1 t N volatised (t of N applied)$^{-1}$),
EF_{ATD} – emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces (0.01 t N-N_2O (t NH_3-N + NO_x-N volatised)$^{-1}$),
44/28 – conversion of N_2O-N to N_2O,
GWP_{N2O} – 100-year global warming potential (= 310) to convert N_2O to CO_2 eq.

For harvesting and collection of crop residues, GHG emissions (E_{hc}) are estimated based on the energy used by the tractors, balers and loading equipment as shown in the equation below. The energy use is calculated based on the work rate of equipment, specific fuel consumption and hours of use to process the required biomass amounts. A distinction is made for crop residue collection in irrigation and dryland farming areas as the work rate in these farming conditions are different.

$$E_{hc} = \sum_j (SEC_e \times t_i/(W_{ei} \times Y_{ci} \times t_i)) \times EF_{fuel} \Big/ (B_{in} \times HHV \times \eta_{CBtP}/3.6) \quad (11)$$

Where:

SEC_e – the specific fuel consumption by type of equipment *e* (GJ h^{-1})
t_i – the duration of activity *j* by farming area type *i* (i.e. dryland or irrigation farming area) (h)
W_{ei} – work rate of equipment type *e* by farming area type *i* (ha h^{-1})
Y_{ci} – crop residue yield by farming area type *i* (t ha^{-1})
EF_{fuel} – CO_2 equivalent emission factor for fuel (diesel) (kg GJ^{-1})

First and second truck transport GHG emissions are calculated using the methodology described in van der Hilst and Faaij [33]. First transport distance is based on the average transport distance from the farm to a central gathering point (CGP) and the average fuel truck consumption. We assume that the truck has an empty return trip. The average first truck transport distance is calculated based on the distribution of biomass in a specific region (taking into account size of district/county, area under crops and yield of feedstock) and the total amount of biomass available for collection in that whole region.

Second transport distance is based on actual distances from specific CGP (typically a regional urban centre/town with connection to a rail network) to the power plant gate. These distances are given in Table A3 in the "Supplementary Material" in the online version of this paper. We also assume an empty return trip for the second transport.

Table 2
Global average GHG emissions of the average N, P_2O_5 and K_2O fertiliser production.

Fertiliser type	Emissions (range)	Unit
N	5.66 (3.42–8.43)	t t^{-1}
P_2O_5	1.36 (0.14–2.15)	t t^{-1}
K_2O	1.23 (0.36–1.91)	t t^{-1}

Source: Kool et al. [92].

GHG emissions from final conversion of biomass to electricity are assumed to be zero since equivalent amounts of CO_2 are absorbed during plant growth. For the reference coal power generation case, the GHG emissions are based on a typical South African coal fired power plant and derived from previous life-cycle analysis (LCA) studies for GHG emissions from electricity generation in South Africa (such as [91] and [97]). To calculate the GHG mitigation costs, the avoided emissions are compared with the additional costs associated with the biomass scenarios (as discussed below).

2.4.2. Electricity production and GHG mitigation costs

Power production costs are calculated for the reference and co-firing scenarios following the methodology detailed in Meerman et al. [98] and Batidzirai et al. [32]. For the reference coal-to-power (CtP) scenario, we assume that the plant is now fully depreciated Camden was commissioned in 1967 [88] and only the operation and maintenance (O&M) costs are taken into account when estimating "fossil" based electricity production costs. The average age of South African power plants is 30 years and the oldest is 49 years old [99]. On the other hand, when co-firing coal and biomass in a coal-biomass to power (CBtP) plant, the "renewable" electricity production costs only take into account the retrofitting investment costs in the fully depreciated coal-thermal power plant. For direct co-firing, the investment cost for retrofitting a coal-fired power plant ranges from 300 to 500 \$ kW^{-1} [100]. The total electricity production costs -COE (\$ MWh^{-1}) are calculated using Equation (12):

$$COE = \frac{\sum_i(\alpha \times I + O\&M + F_c + D_c + T_i)}{[(P_{CtP} \times LF) \times \eta_{CtP}] \times \eta_{CBtP}} \quad (12)$$

Where:

α – the annuity factor (calculated using Equation (13)),
I – power plant investment costs (\$),
$O\&M$ – annual power plant operation and maintenance costs (\$) – assumed to be 4% of *I*,
F_c – annual feedstock costs (\$),
D_c – total pre-processing and densification costs (\$),
T_i – annual transportation costs for supply chain stage *i* (\$),
P_{CtP} – the plant output capacity of the coal-to-power (CtP) plant (MW)
LF – the load factor of the power plant (h y^{-1})
η_{CtP} – power conversion efficiency of a CtP plant (33.4%)
η_{CBtP} – power conversion efficiency of co-firing coal and biomass in a coal-biomass to power (CBtP) plant (%)

The annuity factor is calculated with Equation (13):

$$\alpha = \frac{r}{1-(1+r)^{-plant\ lifetime}} \quad (13)$$

Where *r* is the discount rate (assumed to be 8%).

Co-firing biomass with coal in a CBtP plant necessitates efficiency and capacity de-rating of the CtP plants [101,102]. The lower efficiency is due to sub-optimal supply of fuel to the boilers, given the lower energy density and combustion efficiencies of biomass compared to coal [101,103]. These de-rating effects are much more significant for raw biomass (including pellets) than torrefied pellets (TOPs) [32,98]. At a 30% co-firing rate, the conversion efficiency

(η_{CBtP}) of raw biomass and TOPs is estimated to be 32.4% and 33%, respectively.

GHG mitigation costs ($CO_{2\ c}$) are calculated based on the additional electricity production costs and the total GHG reduction for each co-firing scenario compared to the reference fossil scenario as shown in Equation (14):

$$CO_{2\ c} = \frac{COE_{bio-i} - COE_{coal}}{GHG_{coal} - GHG_{bio-i}} \tag{14}$$

$COE_{bio\text{-}i}$ – cost of electricity production for biomass scenario i (\$ MWh^{-1})
COE_{coal} – cost of electricity production for coal reference scenario (\$ MWh^{-1})
GHG_{coal} – GHG CO_2 eq emissions for coal reference scenario (t MWh^{-1})
$GHG_{bio\text{-}i}$ – GHG CO_2 eq emissions for biomass scenario i (t MWh^{-1}).

2.5. Scenarios (base case and improved case scenarios)

Apart from the Base Case/Business As Usual (BAU) scenario – which evaluates the performance of biomass supply chains under current conditions, we also include an improved case scenario. The improved case scenario explores the potential improvements in biomass supply chain performance when several measures are implemented:

- Increased biomass supply: availability of crop residues can be increased by shifting to no-till cultivation; improved crop yields; improved animal feed conversion efficiency; double cropping; and improved residue collection systems.
- Optimised logistics: supply chain performance can be improved by reducing truck transport; maximising rail transport; and pre-treatment of residues at cost-effective scale.
- Combine biomass streams: different biomass flows such as forestry residues, energy crops, and municipal waste can be integrated into the available feedstock resource.

2.5.1. Increased supply

To improve crop residues availability, several measures are proposed at the farm level, including introducing no-till cultivation, improving animal feed conversion efficiency, improving agricultural management systems, as well as using contractors to collect residues where they are currently burned.

No till cultivation: When residues are left in the field for erosion protection, it is important that these residues are not incorporated in the soil by tillage as this reduces protection. Andrews [17] stresses the importance of tillage-residue interaction when looking into the protection against erosion. No-till without a residue cover can cause more soil erosion than conventional tillage. No-till combined with a residue cover generally results in less erosion than conventional tillage as shown in Fig. 1. Therefore, no-till cultivation increases the net available crop residues compared to conventional tillage.

The base case scenario estimates sustainable SOC levels based on a conventional tilled agricultural production system. The response ratios for SOC under no till cultivation is estimated to be 1.23 for sub-tropical moist soils and 1.17 for sub-tropical dry soils [71]. A response ratio represents the effect of changing agricultural management on SOC and is defined as the ratio of SOC content in no-till cultivation compared to conventional tillage [71]. For South Africa, this is of significance as less than 10% of cropland is currently under no-till [104], and means the potential for improving SOC management is high. Using the response ratios, a new set of SOC requirements can be estimated in the improved scenario for each province as shown in Table 3. However, it is important to note that adoption of no-till can potentially lead to important negative effects such as soil compaction, higher incidence of weeds, crop diseases and pests, problem of volunteer cereals [105]. These disadvantages are discussed in more detail the "Supplementary Material" available in the online version of this paper.

Improved agricultural management and crop productivities: Increased crop productivities lead to increased biomass yields and consequently higher residue availability. For the improved scenarios, we assume 50% and 25% increase for maize and wheat yields respectively by 2030 under dryland farming (following OECD [106]; Perlack et al. [7] and Chum et al. [6]). These yield increases are based on IMAGE (Integrated Model to Assess the Global Environment) model results as detailed in the OECD Environmental Outlook OECD [106] baseline scenario and are in line with the FAO (Food and Agriculture Organisation of the United Nations) projections published in Bruinsma [107]. According to OECD [106], maize and wheat crop yields are expected to improve in OECD countries as well as in BRIICS countries (which include the emerging economies of Brazil, Russia, India, Indonesia, China and South Africa). The projected crop yield increases are also in line with historical trends in yield improvements as shown in Fig. 4. Based on the average trends shown in Fig. 4, maize and wheat yields have increased by 154% and 133% between 1990 and 2010, respectively. In the coming decades, other studies also project an average annual increase in maize yields of 2.4% and for wheat an increase in the range of 2.4–3.4% per year for South Africa [108].

It is important to note that future yields remain uncertain and we provide more discussion on uncertainties of future yields in Section 5.2. To understand the possible developments in maize and wheat production, additional background on maize and wheat farming in South Africa is provided in the "Supplementary Material" available in the online version of this paper.

In this study we have assumed a simple residue to product ratio (RPR) of 1:1 and have not considered the changes in volume of residues that might occur with changes in yield. To fully capture the changes in grain to residue ratios also requires investigating the maize varieties being grown and the possibilities of introducing varieties with higher biomass fraction [7]. Early maturing or short season varieties may have shorter stalks and thus less biomass while the full season varieties may be more suitable for silage [109]. Also according to Gallagher and Baumes [110], modern drought tolerant maize varieties have more extensive roots than traditional varieties, so soil carbon may no longer decline over time with maize production, and thus new modelling would be required to capture the new SOC dynamics.

Improved feed conversion efficiency: Improved feed conversion efficiency in livestock production reduces the amount of crop residues used as livestock feed per unit of product (e.g. kg of meat), thereby increasing net available residues. Improvements can be made by providing more feeding space, providing a better formulated diet, or improving digestibility [112]. Crop residues have low nutrition and cannot form a sole ration for livestock. However, processing can improve their nutrient availability. For South Africa we estimate an increase in feed conversion efficiency of 1.4 based on Smeets et al. [113]. This implies a 30% reduction in the feed requirements for livestock by 2030 (in terms of dry weight feed per kg animal product).

Double cropping: The continuous presence of a growing crop slows carbon decay, allowing SOC to accumulate [34,49,50,104,114].

Table 3
Annual residue requirements to maintain SOC at 2.0% (t ha^{-1}) for different agricultural management systems.

Province	Maize residues			Wheat straw		
	Conventional tillage	No-till[a]	No till + double cropping[b]	Conventional tillage	No-till[a]	No till + double cropping[b]
Northern Cape	5.8	4.7	3.9	6.7	5.5	4.5
Western Cape	4.6	3.7	3.1	5.4	4.4	3.6
Eastern Cape	4.2	3.6	3.0	4.8	4.1	3.4
KwaZulu-Natal	4.7	3.8	3.2	7.0	5.7	4.7
Free State	4.4	3.8	3.1	5.1	4.4	3.6
North West	5.8	5.0	4.1	6.7	5.7	4.7
Gauteng	4.4	3.8	3.1	5.0	4.3	3.5
Mpumalanga	4.1	3.3	2.8	4.6	3.7	3.1
Limpopo	5.3	4.5	3.7	6.0	5.1	4.2

Source: [24].

[a] Under no-till, SOC requirements decrease by 15–19% based on the no-till response ratios 1.17–1.23 [71].

[b] Double cropping results in 11%–24% lower residue requirements for SOC maintenance.

This results in lower residue requirements. When enough water is available to produce two crops in a year, double cropping is a very interesting option. In South Africa, double cropping is generally only possible under irrigation [63]. We assumed double cropping in irrigation areas, and the effect of the double crop is to lower the SOC requirements by 11%–24% (average 17.5% is used in this study). These values are estimates of SOC requirements under a continuous crop and are calculated using the Rothamsted model [24].

Other potential improvement options include returning biomass ashes to the farm, improved crop residue collection systems and employing contractors to collect residues. In irrigation areas, crops residues are sometimes burned since there is limited time to collect the biomass before preparing the fields for the next crop. Farmers burn residues to reduce the amount of the biomass and make the fields more workable. Excessive amounts of crop residues make pre-planting preparation difficult and encourages excessive moisture retention, which hampers the movement of equipment on the fields [115]. However, the continuous burning of stubble residue increases soil erodibility and damages the soil structure [67,68]. Burning also results in CO_2 emissions and air pollution [116], it destroys useful soil micro-organisms and leads to soil nutrient losses [117]. It is therefore beneficial to harvest and utilise crop residues than to burn them. To allow the sustainable removal of crop residues in irrigation areas, contractors can be employed to collect and bale the biomass instead, assuming farmers have limited time and capacity to undertake the same. However, these options were not included in this study due to lack of detailed information.

These measures are grouped into four scenarios for maize and three scenarios for wheat as shown in Table 4.

2.5.2. Optimisation of logistics

The performance of crop residue supply chain logistics can be improved through measures such as:

- reducing road truck transportation
- maximising use of rail system
- Pre-treatment of biomass early in the supply chain to reduce the logistical capacity and improve handling of biomass. This can include pelletising or torrefying the crop residues.
- Strategic location of pre-treatment plants taking into account available biomass volumes and consideration of economies of scale.

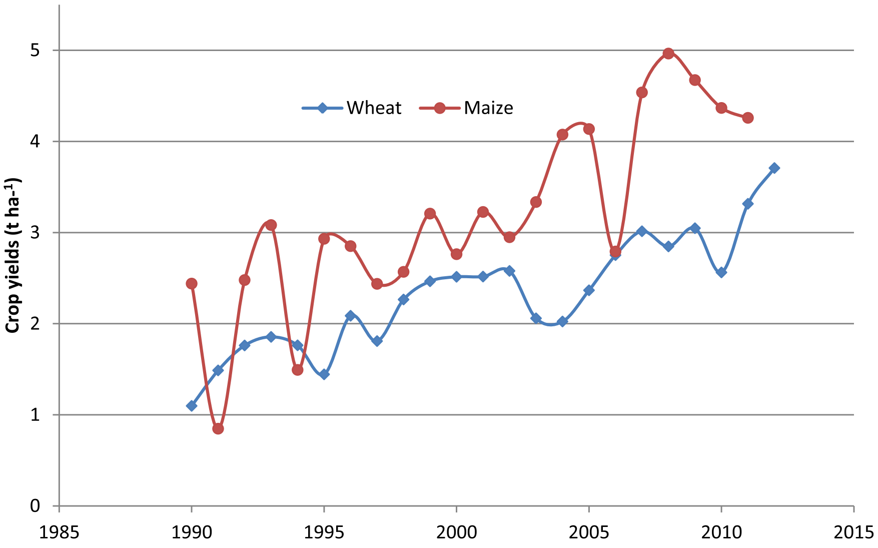


Fig. 4. Trends in average maize and wheat yields in South Africa (1990–2011).
Source: [111].

2.5.3. *Combining biomass flows*

Apart from maize stover and wheat straw, there are other promising biomass resources that can be harnessed in South Africa. These include:

- Forestry waste and residues
- Municipal solid waste
- Sugarcane harvesting and processing waste and residues
- Road side grass
- Energy crops

These different biomass streams can be integrated into a supply system to improve the volumes of biomass available and diversity of resources. It is important to note that the estimation of these other biomass streams is not as detailed as the evaluation of the maize and wheat residues. The methodology is crude and is meant to provide insights into potential of other biomass resources that could be mobilized in South Africa.

2.5.3.1. Estimating forestry waste. To estimate forestry waste, the following equations are used:

$$FR = \sum_i (WP_i \times RGR_i \times RF_i) - U_i \tag{15}$$

Where:

FR – biomass potential of primary, secondary and tertiary forestry residues (t y^{-1})
WP_i – is industrial roundwood production (for wood logging residues), roundwood consumption (for wood processing residues) or pulp and paper production (for pulp and paper waste) (in t y^{-1})
RGR_i – is the residue generation ratio
RF_i – is the residue recoverability fraction
U_i – other applications of wood industry residues and waste (t y^{-1})

Municipal solid waste is estimated based on the product of identified annual waste generation in South Africa and the estimated organic fraction. More details on the methodology and assumptions used to estimate additional biomass streams in available in the “Supplementary Material” in the online version of this paper.

3. Residue availability

3.1. *Volumes and spatial distribution of crop residues -base case*

Table 5 summarises the sustainable maize and wheat residue potential for each region in South Africa. The gross (above ground) crop residue potential from maize and wheat residues is estimated to be about 14.4 million tonnes per annum, but only 6 million tonnes can be removed sustainably from the fields. Additional details on the gross maize and wheat residue potentials are given in Table A4 and A5 in the Supplementary Material of the online version of this paper.

For maize stover, the gross amount of biomass is estimated to be 16 million tonnes per annum as shown in Fig. 5. This includes aboveground biomass (9.7 million tonnes), and 6.3 million tonnes of below ground biomass. About 4.2 million tonnes of maize stover would be required for soil erosion control while 9.3 million tonnes would be required for SOC maintenance. It is important to note that the below ground biomass can only be used for SOC control and is unavailable for removal. Since the amount of residues required to maintain SOC are more than the residues required to prevent soil erosion, some of the aboveground biomass used for SOC maintenance can also be used for erosion control. About 260 thousand tonnes of maize stover are required to meet cattle feed (this figure applies to only those districts which have excess crop residue). The total amount of maize stover required for meet sustainability demands (SOC and feed) is estimated to be 9.5 million tonnes. This results in a net maize stover availability of 5.1 million tonnes per annum.

Similarly, for wheat straw the gross biomass production is estimated to be 1.8 million tonnes (870,000 and 970,000 tonnes of aboveground and below ground biomass, respectively). The amount of wheat straw required to maintain SOC and prevent erosion amounts to about 870,000 and 100,000 tonnes, respectively. About 70 000 tonnes are utilised as livestock bedding. This gives a net wheat straw availability of about 600,000 tonnes per annum.

Overall, the sustainable biomass energy potential from maize and wheat residues is estimated to be about 6 million t y^{-1} (104 PJ). Regions with the highest potential include the Northern Cape, Mpumalanga, and Free-State accounting for about 87% of national residue potential as shown in Table 5 and Fig. 6.

Fig. 6 shows the geographical distribution and relative abundance of crop residue availability in South Africa for all provinces and ‘managerial’ districts (counties). It is apparent most of the potential is located in the centre of the country and there is limited potential of crop residues in western and southern parts of South Africa.

Maize stover is potentially available in larger volumes in South Africa compared to wheat straw. On average, the sustainable potential of maize stover is about 94 PJ while the potential of wheat straw is about 11 PJ. Free State, Mpumalanga and Northern Cape provinces have the highest potential of maize stover (at 32%, 31 and 26% of total potential, respectively). Most of the wheat straw in South Africa can be found in Northern Cape province (about 64% of the national potential).

3.2. *Volumes and spatial distribution of crop residues – improved (future) case*

In the improved case, we analysed the impact of implementing the measures listed in section 2.4.1. As shown in Table 6, the

Table 4
Summary of elements included in improved scenario.

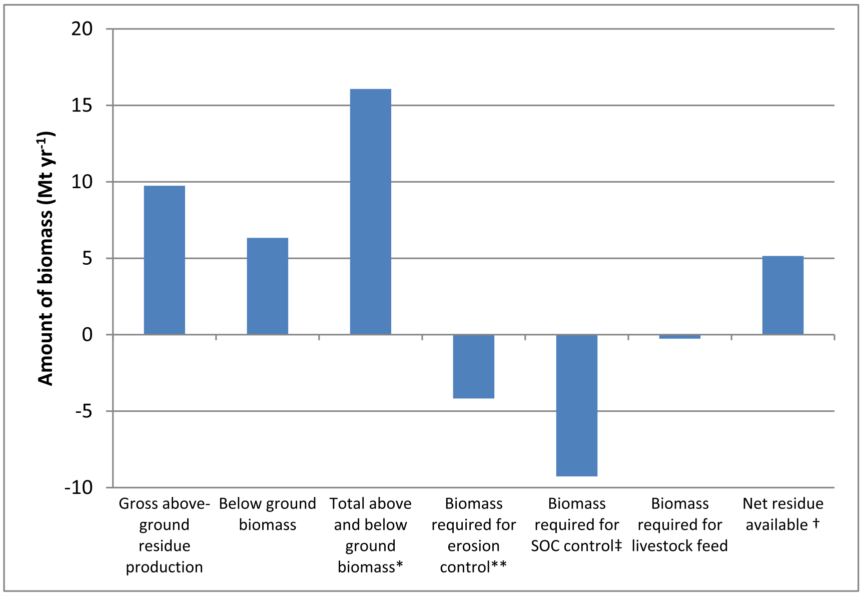
	Improved scenario	Increased crop yields	Not till cultivation	Improved feed conversion efficiency	Double cropping
Maize	1	✓			
	2	✓	✓		
	3	✓	✓	✓	
	4	✓	✓	✓	✓
Wheat	1	✓			
	2	✓	✓	Not applicable	
	3	✓	✓	Not applicable	✓

Table 5
Sustainable maize and wheat residue potential for South Africa (Base case).

Region	Maize stover (Mt)[a]	Wheat straw (Mt)[a]	Total residues (Mt)	Total crop residues (PJ)[b]
Western Cape	0.01	0.002	0.01	0.2
Northern Cape	1.33	0.385	1.71	31.0
Free State	1.65	0.009	1.66	30.1
Eastern Cape	0.03	0.003	0.03	0.5
KwaZulu Natal	0.31	0.025	0.34	6.1
Mpumalanga	1.58	0.019	1.60	29.0
Limpopo	0.01	0.099	0.11	1.9
Gauteng	0.24	0.005	0.24	4.4
North West	0.01	0.055	0.06	1.1
Total	5.15	0.603	5.75	104.5

[a] The average residue to product ratios is assumed to be 1:1 for both maize and wheat [16,45,47,83].

[b] The HHV of the maize and wheat residues is estimated to be 18.2 and 17.8 GJ t^{-1} respectively [74,75].



Notes:
* Total above and below ground biomass is the sum of the gross (above ground) residue production and below ground biomass
** Biomass required for erosion control is derived from aboveground residues only
‡ Biomass required for SOC control is mainly derived from below ground biomass, but where below ground biomass is insufficient to meet SOC control requirements, some aboveground biomass is used to meet SOC requirements. This additional aboveground biomass plays a double function (as it can also be used for soil erosion control). In a situation where soil erosion requirements are smaller than the additional aboveground biomass for SOC control, then all the residue requirements for erosion control are also used for SOC control, thereby reducing the overall residue requirements.
†Depending on the crop production and soil conditions in each district, calculating the net residue available follows different algorithms as described in Section 2.1.3

Fig. 5. Balance of above and below ground biomass vs. biomass required for erosion control, SOC and livestock demand in South Africa.

amount of crop residues more than doubles from 6 million tonnes (104 PJ) to over 13 million tonnes (238 PJ).

The spatial distribution of crop residue availability for South Africa is shown in Fig. 7. It is apparent that the highest increase in residue availability occurs in Free State, Mpumalanga and North West provinces. Maize stover still dominates the crop residue potential in the improved case, accounting for 90% of the total residue potential.

Increased yields have a higher impact on residue availability, especially for maize stover as shown in Fig. 8; for an increase of 50% for maize, the residue availability more than triples (212% increase). For wheat, a 25% increase in yields results in almost triple amount of residue available (180% increase). Introducing no till cultivation results in residue availability increases of 6% for maize stover and 123% for wheat straw. Improved animal feed conversion efficiency does not have a significant impact on maize stover availability, contributing only 0.9% increase. Double cropping results in an increase in wheat straw availability of about 108% but results in no increase for maize stover. The latter is due to the fact that there are high amounts of below ground biomass in maize irrigation areas and any reduction in SOC requirements are not beneficial overall. For wheat, any reduction in SOC requirements is beneficial because the below ground biomass is available in smaller quantities.

4. Logistics

4.1. Cost of maize and wheat residue production

4.1.1. Residue Production costs— base case

Table 7 shows the breakdown of various costs elements for crop residues collection in a typical dryland farm.

Overall the cost of collecting, baling and storing maize stover at

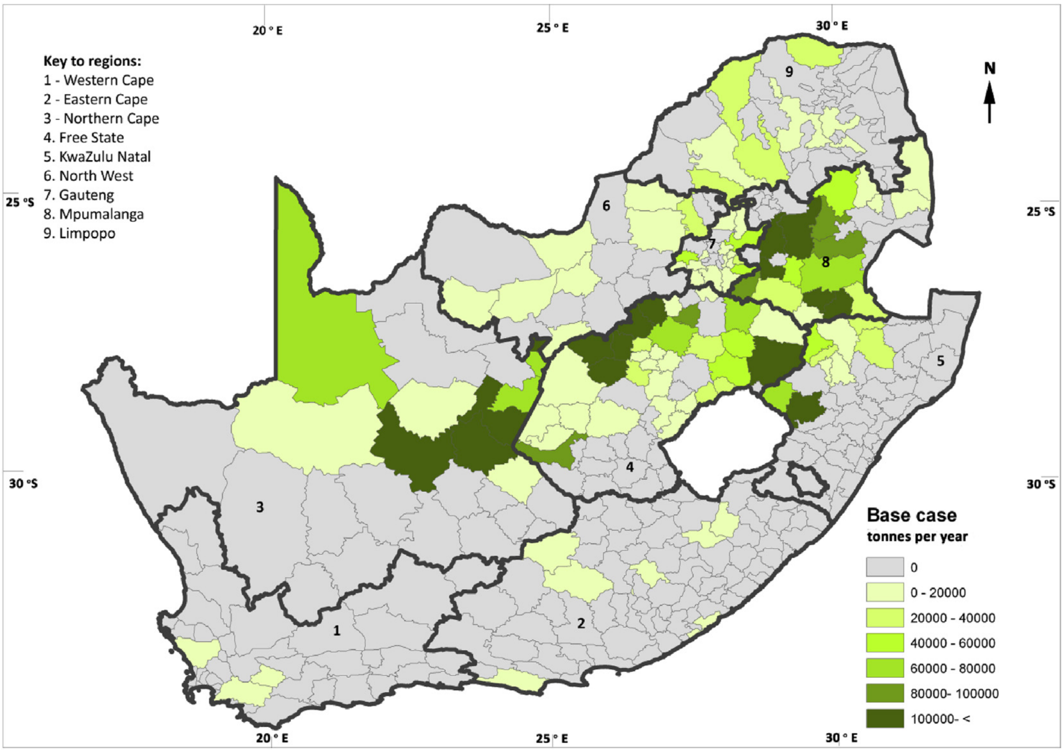


Fig. 6. Distribution of crop residues by district in South Africa – Base Case. The map shows total biomass available in each district in tonnes per year calculated according to the system in Fig. 5.

the farm is estimated to be about 1.5 $ GJ^{-1}. Compensation for the farmers for lost nutrients dominates the cost of maize stover at the farm accounting for 58% of total costs (or 0.87 $ GJ^{-1}). Baling is also a very important cost element representing 29% of the total costs. A 10% farmer profit margin on direct costs is allowed in the estimated direct costs and this represents about 4% of the total costs.

The cost of maize stover at the farm gate on a typical irrigation farm (at 1.26 $ GJ^{-1}) is about 16% lower than the cost at a dryland farm (1.5 $ GJ^{-1}). This is mainly influenced by the higher crop productivities and corresponding higher residue availability in irrigation farms. The relative contribution of farmer nutrient compensation is much higher at 69% of total costs.

The costs of wheat straw at the farm gate are higher compared to maize stover due to the lower wheat yields and different operations involved in the collection, baling and storage. Wheat straw at a typical dryland farm costs about 1.5 $ GJ^{-1} assuming a yield of 2 t ha^{-1}. Baling dominates the overall wheat straw costs at 43% (or 0.66 $ GJ^{-1}) and farmer nutrient compensation accounts for 41%.

Wheat straw costs in irrigation areas are 36% lower (at 0.64 $ GJ^{-1}) than in dryland farms. Nutrient compensation dominate overall costs at 54% while baling costs still accounts for a higher percentage of the overall costs (at 32%).

Fig. 9 shows the combined crop residue cost supply curve for South Africa. Overall, about 7% of crop residues (6.8 PJ) are available at costs below 1 $ GJ^{-1} at the farm gate while 34% of the residues are available at costs below 1.2 $ GJ^{-1}. About 96% of the residues are available below 1.5 $ GJ^{-1}.

4.1.2. *Residue production costs – improved case*

In the improved case scenarios, about 80–85% of the biomass (185–193 PJ) is available at the farm gate at cost below 1.3 $ GJ^{-1}. In addition, about 99% of the biomass is available at costs below 1.5 $ GJ^{-1}.

4.2. *Supply chain analysis to the conversion plant*

4.2.1 Base Case

Fig. 11 shows the combined cost supply curve for the maize and

Table 6
Sustainable maize and wheat residue potential for South Africa (improved scenario).

Region	Maize stover (Mt)	Wheat straw (Mt)	Total crop residues (Mt)	Total crop residues (PJ)[a]
Western Cape	0.02	0.45	0.46	8
Northern Cape	1.77	0.50	2.27	41
Free State	3.90	0.17	4.07	74
Eastern Cape	0.07	0.01	0.08	1
KwaZulu Natal	0.60	0.04	0.65	12
Mpumalanga	3.02	0.03	3.05	55
Limpopo	0.08	0.15	0.23	4
Gauteng	0.52	0.01	0.53	10
North West	1.68	0.11	1.78	32
Total	11.66	1.45	13.12	238

[a] The underlying data is given in online “Supplementary Data”.

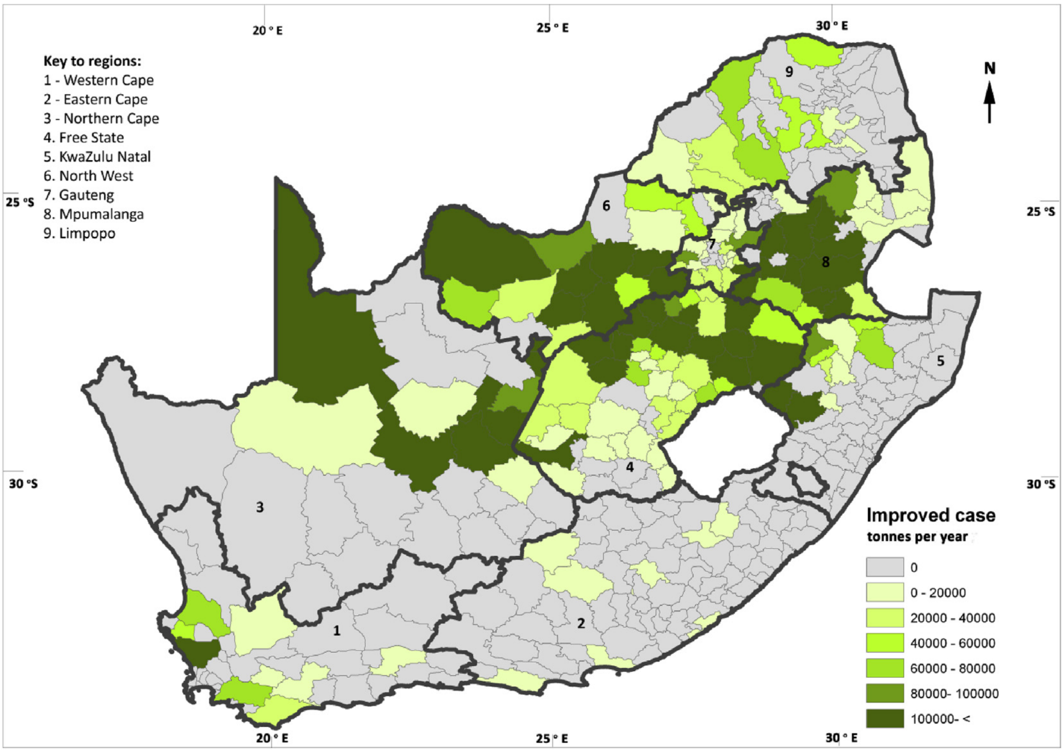


Fig. 7. Distribution of crop residues by district in South Africa – improved case.

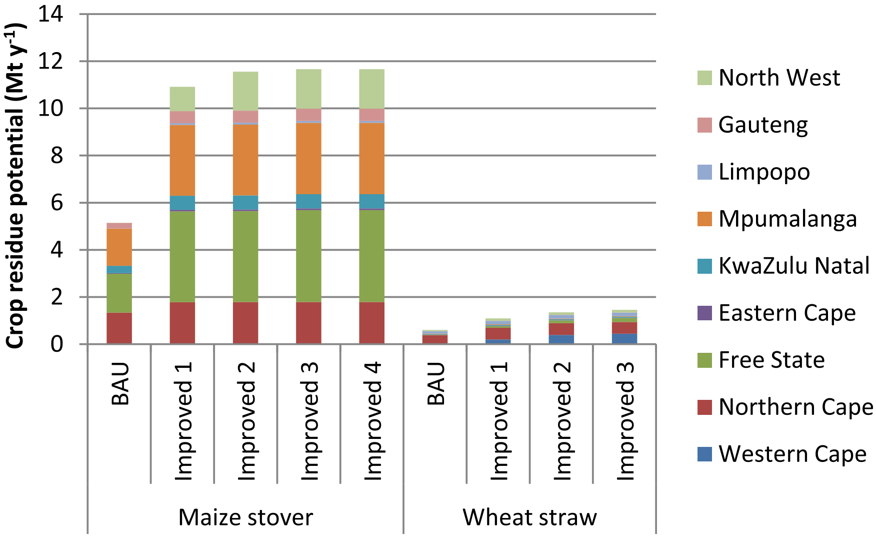


Fig. 8. Comparison of crop residue potential by scenario.

wheat residues at the factory gate delivered to the final energy conversion plant. These costs include the crop residue harvesting, collection, baling and storage at the farm, transport to a local distribution point as well as long distance transport by truck to the conversion plant.

On average, crop residues in South Africa are delivered at a cost of about 7.1 \$ GJ^{-1} – this is a weighted average cost for biomass from all regions. About 11% of the biomass is delivered at the conversion plant at less than 3 \$ GJ^{-1}, whereas about 36% can be delivered at less than 5 \$ GJ^{-1}. About 82% is delivered at less than 10 \$ GJ^{-1} and only 5% of the biomass is delivered above 15 \$ GJ^{-1}.

4.2.2. *Improved case*

The optimised scenarios depict an improved future situation characterised by higher biomass availability and use of rail transport instead of trucks for the second long distance transportation phase of the supply chain, see Table 8. We have also included a sensitivity analysis on the impact of future improvements (up to 2030) in pre-processing performance (indicated in Fig. 10 as 'future' TOPs and pellets scenarios). These improvements assume a modest technological learning of 5% for pre-processing, and result in considerable decrease in pre-processing costs for TOPs but marginal cost reduction for traditional pellets (based on Batidzirai et al. [118]).

Fig. 10 compares the weighted average supply costs of crop

Table 7
Breakdown of current crop residue costs at the farm gate in dryland farming ($ GJ^{-1}).

Activity/cost element[a]	Maize stover[b]	Wheat straw[b]
Slashing	0.020	–
Raking	0.024	0.039
Baling	0.428	0.657
Forwarding	0.015	0.025
(Un)loading	0.019	0.032
Labour	0.003	0.005
Storage	0.059	0.060
Farmer compensation	0.865	0.618
Subtotal	1.434	1.436
Profit margin	0.057	0.082
Totals	**1.49**	**1.5**

[a] Equipment investment and operational costs are given in online "Supplementary Data". Interest rates are assumed to be 8% and exchange rate is 9 ZAR: USD at the time of the study.

[b] Assumes slasher (2 m, 35 kW) at 4.9 $ h^{-1}, Rake (7.2 m, 26 kW) at 7.7 $ h^{-1}, Bale fork loader (2.7 m lift – 500 kg) at 1 $ h^{-1}, 10 tonne flatbed trailer at 4.1 $ h^{-1} and 44 kW two-wheel drive tractor at 11.7 $ h^{-1}; 95 kW Large square baler at 281 $ h^{-1} and 123 kW four wheel drive tractor at 46.3 $ h^{-1}; Labour at 2.5 $ h^{-1} [68]. For wheat operations, the slasher combination is not required.

residues delivered to the conversion plant for the various scenarios considered in this study. At current conditions, the pellet supply chain has the lowest cost biomass (4.1 $ GJ^{-1}) followed by TOPs (5.7 $ GJ^{-1}). As TOPs processing costs decline in the future, average delivered costs of TOPs are expected to decrease to 4.7 $ GJ^{-1}. The Base Case (with raw biomass bales) has the highest biomass delivered cost of 6.9 $ GJ^{-1} compared to the improved case supply chain (6.6 $ GJ^{-1}). This is because train transport becomes more efficient with larger volumes of biomass associated with the improved case (raw bales).

Despite the additional pre-treatment costs of biomass (13.3 $ t^{-1} for pellets and 52.4 $ t^{-1} for TOPs), the pellet chain and TOPs chain deliver lower cost biomass to the conversion plant as shown in Figs. 11 and 12. For pellets, about 24% of the biomass is delivered at costs below 3$ GJ^{-1} while only 12% of TOPs are delivered at costs below 4$ GJ^{-1}. About 87% of pellets and 61% of TOPs are delivered below 5 $ GJ^{-1}, compared to only 42% for the raw biomass scenarios.

About 32% of pellets are available at the factory gate between 5 and 10 $ GJ^{-1}, corresponding amounts of TOPs and raw biomass are 59% and 51% respectively.

Similar trends are also exhibited by the scenarios that employ rail for the second transport as shown in Fig. 12. About 24% and 14% of pellets and raw bales respectively cost below 3 $ GJ^{-1} at the factory gate. For TOPs, 12% is delivered at costs below 3 $ GJ^{-1}. At 5$ GJ^{-1}, there are 42% of raw bales, 87% of pellets and TOPs. About 92% of pellets based biomass is delivered at the factory gate at costs below 6$ GJ^{-1}, while corresponding values for TOPs and raw bales are 89% and 60% respectively. Nearly all pellets and TOPs based biomass (99%) are delivered below 10 $ GJ^{-1}.

In absolute terms, only 42 PJ is delivered in the BAU below 5$ GJ^{-1} compared to 96 PJ (for raw biomass-improved scenario 1), 190 PJ (pellets –improved scenario 2) and 168 PJ (TOPs-improved scenario 3). Therefore, considering co-firing 30% biomass at Camden (1600 MW), this would require 36 PJ biomass feedstock and at current conditions, there is adequate biomass below 5 $ GJ^{-1} to meet this demand. For this particular power plant, supplies can therefore be built up over time with changing demand and improvements in supply.

4.2.3. *Distance supply curve*

Fig. 13 shows the distance supply curve for maize and wheat residues with reference to the final energy conversion plant (Camden power plant). About 14% of biomass can be sourced within 100 km radius of the conversion plant while 30% is within 200 km. Most of the biomass (82%) is within 600 km from the conversion plant and which especially would be suitable for rail transport.

4.3. *Combined biomass streams*

Apart from maize and wheat residues, other potential biomass resources in South Africa include sugar cane residues, forestry industry residues and municipal solid waste. The detailed methodology and assumptions for calculating the potential biomass from these streams is provided in the online "Supplementary Material". The biomass energy potential of forestry residues is about 189 PJ. See Fig. 14. Forestry residues resources include primary forestry residues (41 PJ), secondary forestry residues (17 PJ), tertiary forestry residues and waste (70 PJ) and wood chips (61 PJ). Residues from sugar cane plantations and from cane processing (bagasse) are estimated to be between 19 and 32 PJ (the higher end assuming state of the art energy conversion equipment is installed in sugar mills thereby increasing efficiency of steam and electricity production). There is an estimated 4.5 million dry tonnes of organic waste from municipal solid waste that can be utilised for energy

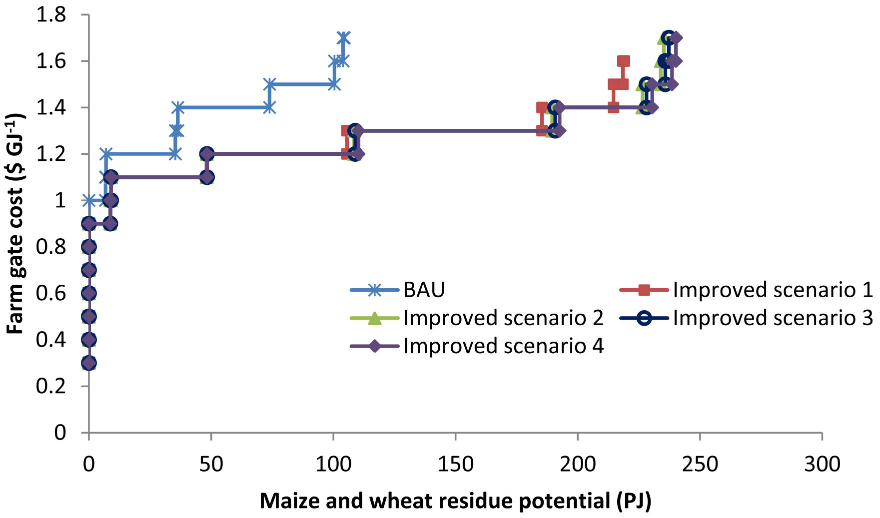


Fig. 9. Cost supply curve of combined maize and wheat residues at the farm gate (BAU vs. improved scenarios).

Table 8
Summary of elements included in improved logistics scenarios.

Scenario	Biomass type	Pre-treatment	Transport mode	
			Truck	Rail
BAU	Bales-raw	–	X	X
Improved 1	Bales-raw: this scenario assumes crop residue bales are transported in their raw form with no further pre-treatment	–	X	X
Improved 2	Pellets: this scenario assumes the crop residues are pre-processed into pellets to achieve higher energy density before long distance transportation to the conversion plant	X	X	X
Improved 3	TOPs: this scenario assumes residues are pre-processed into torrefied pellets	X	X	X
Improved 4	Pellets: this scenario assumes improvements in future pelletising performance through technological learning	X	–	X
Improved 5	TOPs: similarly this scenario assumes technical and economic improvements in torrefaction	X	–	X

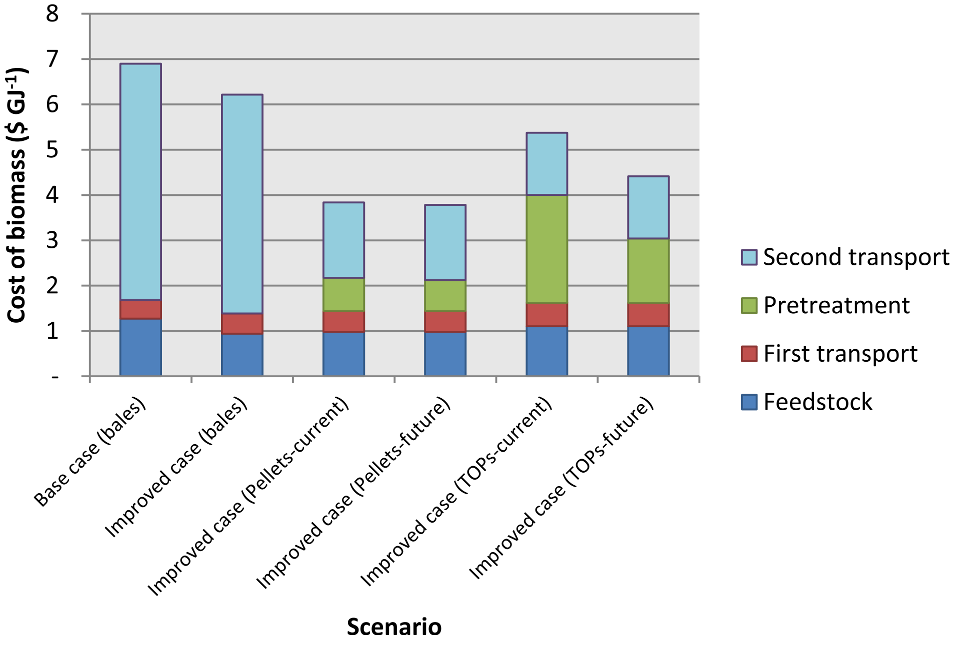


Fig. 10. Breakdown of average cost elements for biomass delivered at the conversion plant gate.

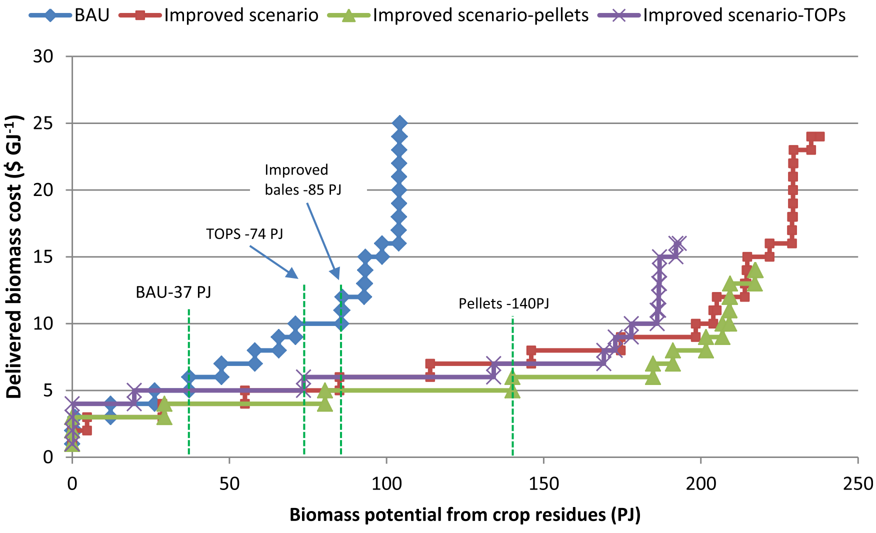


Fig. 11. Cost supply curve for maize and wheat residues delivered to the conversion plant (BAU vs. improved truck scenarios).

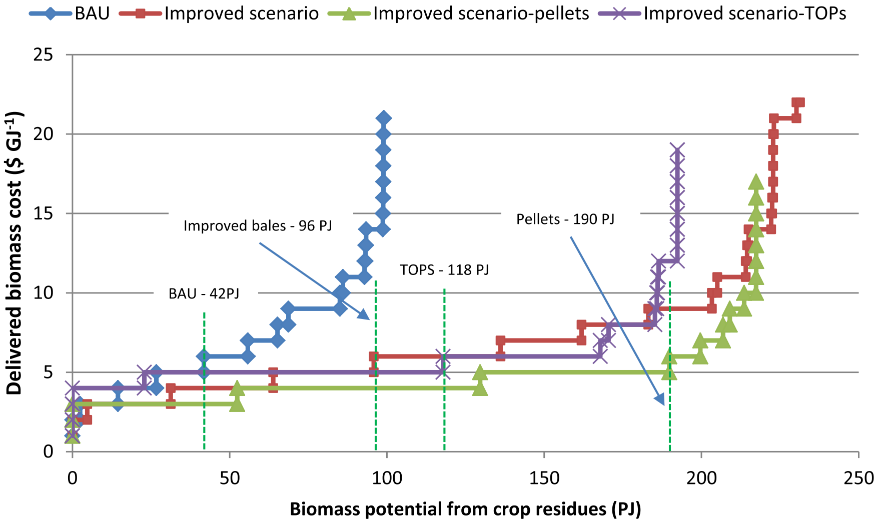


Fig. 12. Cost supply curve for maize and wheat residues delivered to the conversion plant (BAU vs. improved rail scenarios).

which gives a potential of about 81 PJ. Overall, the biomass energy potential in South Africa ranges from about 400 to 550 PJ. This potential excludes the biomass potential from energy crops and from public grasslands and road side grasses. These two resources require more elaborate analysis to provide estimates of sustainable potential. Some preliminary estimates from other studies (e.g. Wicke et al. [119]) show that South Africa has potential land availability of about 1.3 million ha (mainly semi-arid and former homelands) which can produce energy crops in the order of 2.5 EJ. This is equivalent to the total coal energy use for power generation in South Africa [120].

About 4–5% of the total biomass potential is located within 100 km of the conversion plant, while 30% is within 250 km. About 50% of the biomass is located less than 350 km from the conversion facility and 80% is within 550 km.

4.4. *Greenhouse gas (GHG) balance and mitigation costs*

GHG emissions at the various supply chain stages are based on the fossil energy use at each stage and the corresponding emission factors. For feedstock production, the energy balance is shown in Table 9. For post farm-logistics, the energy use for pre-processing is given in Table 10, while the energy use for transport are given under Table 11.

Table 11 summarises the GHG balance for selected biomass supply chains compared to CO_2 equivalent GHG emissions for a typical South African coal fired power plant (assumed to be 993 kg MWh^{-1}) [90,91]. Key differences in GHG emissions for the biomass scenarios are related to second transport (raw bales incur about 2.5 times more GHGs (CO_2 eq.) compared to pre-treated biomass) and pre-treatment (pelletising and torrefaction stage result in about 0.2 t MWh^{-1} emissions). Compared to the reference coal scenario, biomass co-firing reduces total CO_2 eq. GHG emissions by about 0.57–0.68 t MWh^{-1}. The power production costs for the depreciated reference coal are estimated to be about 10.3 $ MWh^{-1} while for the co-firing scenarios power production costs are between 23 and 31 $ MWh^{-1}. Given the additional costs of between 13 and 21 $ MWh^{-1} for the co-firing scenarios, the cost of GHG mitigation (per unit of CO_2 eq) is estimated to be 31 $ t^{-1} for co-firing raw bales, 23 $ t^{-1} for pellets and 29 $ t^{-1} for TOPs.

It is also clear that co-firing biomass results in lower power generation costs compared to other renewable technologies (which are estimated to be up to over 400 $ MWh^{-1} for solar thermal). Already there is significant investment in renewable electricity generation in South Africa. In the second quarter of 2013 alone, South Africa spent 950 $ million on renewables, mainly on wind farms, making the country one of the global leaders in renewables investment [135,136]. The Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) has resulted in renewable energy project investment commitments of about $14 billion with a combined nameplate capacity of 6327 MW since 2011 [137]. Given this investment drive in renewables and the competitiveness of biomass co-firing, co-firing biomass could therefore play an important role in future renewable electricity generation in South Africa.

5. Discussion

In this section, we discuss briefly the potential impacts of the uncertainty inherent in some of key factors that influence the potential of biomass availability as well as the viability of mobilising this resource for energy application. These factors include soil organic carbon, yield improvements, residue market price impacts, transport and pre-treatment costs.

5.1. *Soil organic carbon*

We assumed in this study that the required soil organic carbon level for sustainable crop production for all soil types is 2% in the top 20 cm (within the range of 1%–3%) [36,61]. This is considered high, especially for South Africa [63]. In general, agricultural soils currently have very low organic carbon levels (<0.5%) [71,144,145]. No research has been conducted to date to establish the sustainable levels of SOC for different South African soils, and thus also considerable uncertainty exists on the required SOC for different agro-ecological conditions in the country. The uncertainties result from the differences in SOC storage under different soil texture, climate, vegetation and land use/management conditions [146,147]. Due to higher clay content, heavier soils are generally able to physically protect SOC from decomposition and well aggregated soils can protect SOC from losses due to erosion. In contrast, a more rapid turnover of SOC occurs in sandy soils with little or no clay content [148]. Newly incorporated organic material is also about seven times more decomposable than inherent SOC [149].

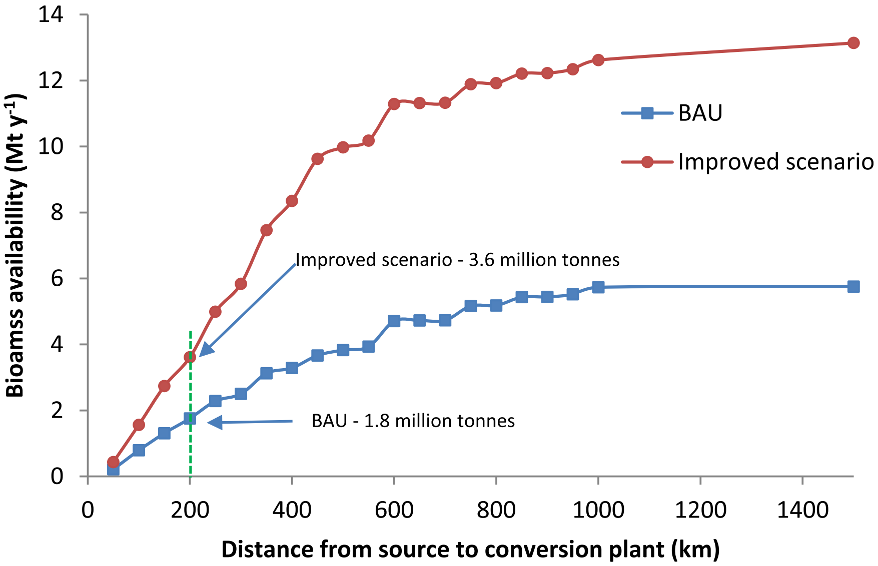


Fig. 13. Distance supply curve for maize and wheat residues relative to the conversion plant.

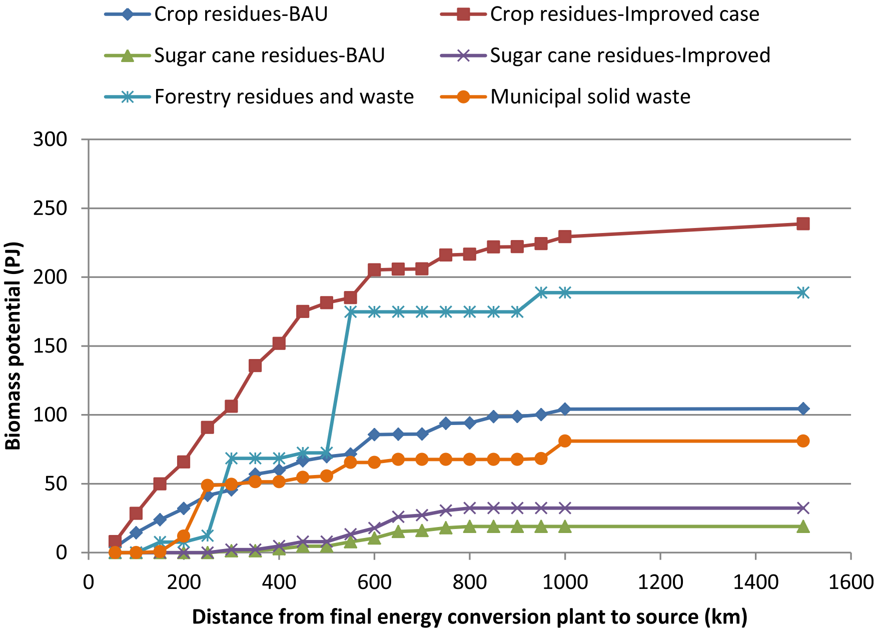


Fig. 14. Distance supply curve for selected biomass resources in South Africa relative to the conversion plant.

5.2. *Yield improvements*

Estimating future crop yields is based on crop yield models and scenario assumptions on progress in agricultural management and this typically results in a range of values reflecting the inherent uncertainty in crop yield projections [150]. Approaches to estimating improvements in crop yields take into account factors such as land quality, and environmental and management factors. These factors are highly uncertain and consequently the yield increase estimates also contain considerable uncertainty. This typically also requires detailed data to model properly [151,152]. Since such studies have not been conducted for South Africa, we have to rely on global models and estimates of yield improvements for both maize and wheat.

The yield increases used in this study are based on results from the IMAGE model. IMAGE employs the FAO agro-ecological zones (AEZ) crop growth model to calculate ‘constraint-free rainfed crop yields’ based on local climate as well as soil-specific conditions such as nutrient retention and availability, level of salinity, alkalinity and toxicity [106,153]. Crop yields are adjusted by a management factor that accounts for the future impact of breeding, a higher harvest index, use of irrigation and fertilisers, general (bio)technological improvements and the effect of CO_2 fertilisation [150]. This ensures that key factors that influence future yield levels are taken into account. However, despite its comprehensive outlook, the accuracy of IMAGE results relies on the quality of the various input datasets and especially the world soil maps could be a source of inaccuracies/uncertainties.

While these crop yield estimates given in this study are technically feasible within the context of South Africa’s agro-ecological and technological capacity, the actual short to medium term yield improvement would depend on the rate of improvement in

Table 9
Energy use for biomass harvesting.

	Crop	Activity	Duration of activity (h)[b]	Fuel use (L h^{-1})[b]	Total fuel use (L)	Biomass processed (t h^{-1})	Specific energy consumption (L t^{-1})	Total energy use (MJ t^{-1})[a]
Dryland	Maize	Baling	5.2	22.14	115.1	42	2.7	99.73
		Raking	4.8	7.92	38.0	42	0.9	32.96
		Total					3.6	132.70
	Wheat	Baling	3.86	22.14	85.4	28	3.1	111.06
		Raking	3.57	7.92	28.2	28	1.0	36.71
		Shredding	2.58	7.92	20.4	28	0.7	26.52
		Total					4.8	174.29
Irrigation	Maize	Baling	5.2	22.1	115.1	72	1.6	58.18
		Raking	4.8	7.9	38.0	72	0.5	19.23
		Total					2.1	77.41
	Wheat	Baling	3.9	22.1	85.4	49.5	1.7	62.82
		Raking	3.6	7.9	28.2	49.5	0.6	20.76
		Shredding	2.6	7.9	20.4	49.5	0.4	15.00
		Total					2.7	98.59

[a] Diesel – 36.4 MJ L^{-1} [121].
[b] Source [68].

Table 10
Pre-processing energy requirements for TOPs and WPs supply chains (MJ GJ^{-1}).

Supply chain stage	Fuel type	WPs	TOPs
Chipping[a]	Electricity	3.13	3.22
Drying	Electricity	4.52	–
	Biomass	8.85	–
Torrefaction	Electricity	–	9.78
	Biomass	–	104.67
Milling	Electricity	6.35	1.64
Pelletising[b]	Electricity	15.66 [122,123]	7.20

Source [124,125].
[a] While woody biomass is sized by chipping, herbaceous biomass bales are cut into short pieces or shredded (to about 25–50 mm) using a knife mill [126] or tub grinder [123,127]. Further grinding of the shredded or chopped biomass (to an average size of 1–3 mm) is attained using a hammer mill [128], disc refiner, pin mill or chain mill [129,130]. Mani et al. [127] give grinding energy requirements of 23–62 kWh t^{-1} for biomass particle sized to 0.8–3.2 mm.
[b] Van Dam et al. [131], Sikkema et al. [132], Mani [133] and Uasuf [134] give a range of values for electricity use of 33–119 kWh t^{-1}. We use an average figure of 74 kWh t^{-1} pellet.

agricultural management as well as environmental conditions. A significant yield gap exists between South Africa and other regions of the world. For instance, average maize yield for South Africa is 4.3 t ha^{-1} compared to 9.2 t ha^{-1} for the US [154]. These yield levels for South Africa only account for the commercial farming sector and scope also exists for the millions of small-holder farmers to improve their crop yields.

To close the gap between current and potential yields, there is need for continued development in agronomy including pest, disease and weed management. Efficient water usage (through for instance drip irrigation), better seeds and innovative farming systems could significantly improve cereal productivity beyond current levels [150]. The deployment of new biotechnology in seed varieties that tolerate toxicity and abiotic extremes as well as resistances to pests and diseases could improve yield. These measures could result in higher crop production costs, and thereby rendering them unattractive. However, additional income from residue sales could be invested in biomass collection and other changes required at the farm. A cost benefit analysis could be conducted to assess the economic impacts of such measures, but for this study, the price effects of these measures were not assessed.

It is important to take into account the biophysical yield ceiling for the cropping scenarios in South Africa. A key challenge for South Africa's agriculture sector is water scarcity (currently most of the crops are rainfed) [149]. Other factors may also contribute to yield plateaus, including erratic weather patterns, land degradation, shifting of production zones to more marginal areas, policies on the use of fertilizers and pesticides, and lack of agricultural research and development [155].

5.3. *Competing markets*

Currently crop residues are used as livestock fodder and bedding in South Africa. There are also other potential crop residue applications such as bio-based materials and synthetic fuel production. In South Africa, synthetic fuel production is a potential alternative application for crop residues. Since the markets for these competing applications do not yet exist, the impact of a developing residues market remains uncertain. Many studies use the opportunity cost of residues as an indicator of its potential value. The opportunity cost of using crop residues for energy is the value foregone by not using them in a competing application (or the price paid for residues by competing uses). For example, the residue market is expected to reflect the forage value of residues and prices for the close substitute, hay, when the unused residue is exhausted in a local area [15]. As the market develops, residue supply is expected to increase in value when all harvested residue is used by industry. This would lead to an increase in the cost of crop residues and consequently the cost supply curves would shift. The effect of growth in the residue market and market dynamics remains largely uncertain and this can be subject of further research.

For South Africa, it is difficult to determine the true price of residues or animal uses since the residues are typically traded informally. In the US, the opportunity cost of residues are estimated at 51.3 $ t^{-1} for maize stover and 26 $ t^{-1} for wheat straw [15]. To make more accurate estimates of the opportunity costs of crop residues would require more analysis.

5.4. *Transport and pre-treatment costs*

Transport costs are also likely to be variable as they are strongly dependent on oil prices, which are in turn volatile. Current crude oil prices are around 16 $ GJ^{-1}, but since 2011, oil prices have fluctuated between 12 and 21 $ GJ^{-1} [156]. Long term oil costs (up to 2030) are estimated to be 23 $ GJ^{-1} [157]. Given the volatile nature of oil prices, transport costs can also be expected to fluctuate and closely follow the oil price trends.

Regarding pre-treatment, pelletising is a mature biomass pre-processing technology while torrefaction is still being developed and commercialisation is expected within the coming decade.

Table 11
GHG balance and mitigation costs of biomass co-firing scenarios.

	Reference scenario	Biomass co-firing scenario			Units
	Coal	Bales	WPs	TOPs	
Feedstock harvesting[c]	–	0.016	0.016	0.016	t MWh^{-1}
Nutrient compensation	–	0.101	0.101	0.099	t MWh^{-1}
First transport[c, d]	–	0.003	0.003	0.003	t MWh^{-1}
Pre-treatment	–	0	0.219	0.187	t MWh^{-1}
Second transport[c, d]	–	0.201	0.084	0.078	t MWh^{-1}
Conversion[a]	0.99	0	0	0	t MWh^{-1}
Total GHG emissions	0.99	0.32	0.42	0.38	t MWh^{-1}
GHG emission reduction	–	0.67	0.57	0.61	t MWh^{-1}
Emission reduction	–	68%	57%	61%	
Total logistics costs	–	21.93	13.75	18.69	\$ MWh^{-1}
Conversion costs[b]	10.27	9.49	9.49	9.31	\$ MWh^{-1}
Total power production costs	10.27	31.42	23.24	28.01	\$ MWh^{-1}
Additional costs	–	21.15	12.96	17.73	\$ MWh^{-1}
Mitigation costs (per unit CO_2 eq avoided)	–	31.47	22.72	29.04	\$ t^{-1}

Levelised power generation costs of other technologies	Average costs (US)[e]	Costs range (US)[e]	Cost range (Germany)[f]	
Wind	86.6	73.5–99.8	67–131	\$ MWh^{-1}
Wind – Offshore	221.5	183.0–294.7	155–374	\$ MWh^{-1}
Solar PV	144.3	112.5–224.4	164–401	\$ MWh^{-1}
Solar Thermal	261.5	190.2–417.6	–	\$ MWh^{-1}
Hydro	90.3	58.4–149.2	35–103	\$ MWh^{-1}

[a] EF of diesel (per unit CO_2) – 0.073 kg MJ^{-1} [140].

[b] Emissions are based on energy use for transport (assumed 18.2 MJ km^{-1} for a 36 tonne truck; and 240 MJ km^{-1} for 1000 tonne electric rail system – [141]), transportation distances including empty return trip and number of trips per year.

[c] Includes emissions from power plant operations [138].

[d] This assumes a depreciated pulverised coal power plant of 1600 MW capacity at an investment cost of 2000 \$ kW^{-1} [139] interest rate of 8%, plant lifetime 30 years, efficiency of 33.4%, load factor of 7000 h. Only operational costs are assumed for the coal plant. Co-firing is assumed to be at 30% (energy basis) and additional investment are estimated to be 400 to 600 \$ kW^{-1} [100]. Average domestic coal prices are assumed to be 1.9 \$ GJ^{-1} [120].

[e] US-EIA [142].

[f] Veiga et al. [143].

Therefore information used to evaluate technological performance is based on demo and pilot scale plants. In the long term (by 2030), production costs of TOPs are expected to decline by over 50% due to scaling up and technological learning. TOPs production costs are expected to fall to within an average range of 2.1–4.1 \$ GJ^{-1} [118].

5.5. *Preconditions to secure sustainable crop residue based biomass supplies*

A number of issues need to be addressed to ensure that a successful and sustainable crop residue supply system can be established in South Africa. These issues include investment in equipment at the farm and infrastructure along the supply chain, pre-treatment of crop residue and changes in the agricultural management on the farms.

Investment on the farm for harvesting, collecting and storing crop residues: Special crop residue collection equipment is required at each farm to implement any biomass production for supply to the market. It is uncertain how many farmers have crop residue collection equipment in South Africa; only those farmers that already have hay, silage or lucern enterprises are expected to own the appropriate equipment. Therefore, most farmers would have to invest in new equipment or hire contractors.

Transport infrastructure: Moving large quantities of low density biomass will require adequate road and rail capacity to accommodate the volumes of additional commodities on the transport system. This additional burden on the transport system must be supported by sufficient investment in the physical ability of the road and rail network to absorb additional traffic movement. If there is inadequate rail wagon and truck capacity, additional investment will be required. For long term competitiveness of crop residue supply, the rail network would have to absorb most of the traffic. Road truck transport is generally not suitable for long distance transportation of low value commodities. It will also be necessary to establish appropriate storage facilities at various points along the supply chain.

Pre-treatment: To improve the performance of crop residue supply chains, it is necessary to establish pre-treatment facilities in the various biomass production regions. There are a number of possible pre-treatment methods that can be used to upgrade the energy density of crop residues and reduce their handling and logistic costs. Baling is already one method to increase the energy density and improve the handling, but the energy density is still low (at less than 0.2 t m^{-3}). Typical pre-treatment methods for biomass include pelletisation, briquetting, torrefaction and pyrolysis oil production. These pre-treatment facilities can be established at a local level or in centralised locations depending on the opportunities for economies of scale for each particular technology. Traditional biomass pellets and briquettes are well established technologies that can be readily implemented in South Africa. Torrefaction however is still being developed, but it can potentially improve the supply chain performance significantly as its characteristics (when densified to pellets) are closer to coal.

Agriculture management: Maintaining site specific sustainable removal rates is critical for ensuring long term agricultural production is not compromised by excessive residue removal. It would therefore be necessary to conduct localised soil analysis and account for various local environmental and socio-economic factors to enable the establishment of sustainable residue removal rates. From the analysis in this study it is clear that to obtain higher volumes of crop residues, it would be necessary for farmers currently on conventional tillage to switch to no-till farming as this increases the amount of residues that can be available for removal. More scientific analysis also needs to be conducted and shared with farmers and other stakeholders to ensure that they are well informed on the sustainability of biomass supply.

Organisation of supply chain: The practical implementation of a residue supply system from farming areas to final conversion facilities involves many stakeholders and needs to be organised efficiently to minimise potential supply risks. More investigations need to be conducted to assess the risks in security of supply as well as farmer consultation on their willingness to commit to long term supply contracts. It is important for power operators to enter into biomass supply contract agreements with farmers so as to ensure security of supply. These take-off agreements must specify the price, quality, timing of deliveries and expected volumes of biomass.

5.6. Other challenges and barriers to implementing co-firing with agricultural residues

Despite the positive technical, economic and environmental performance of co-firing with crop residues, there are currently no known commercial ventures in South Africa. This is due to several factors, including economic (especially the abundant availability of cheap coal in South Africa), environmental (e.g. lack of penalties) and technical (e.g. fuel integration risks).

As a fuel for electricity generation, biomass from crop residues compete directly with abundantly available and cheap coal in South Africa current coal costs are between 0.8 and 1.2 \$ GJ^{-1} [158]. In addition to using a more costly feedstock, co-firing requires retrofitting current facilities with biomass handling and processing functions which add to operational costs. There is therefore little incentive for power producers to co-fire coal with biomass, also given that there are currently no incentives to deliver ‘green’ electricity. However this could change as current discussions around carbon taxation and GHG abatement are implemented [159]. The only policy instrument that could promote the use of crop residue is the feed-in-tariff system, which also applies to sustainable biomass energy [160]. Currently there is no formal market for crop residues and its pricing remain uncertain and spontaneous.

For utility-scale power generation projects, securing consistent, year-round supplies of sufficient volumes of biomass is important for generating firm power [161]. But maize and wheat residues are available seasonally, and there are potential fluctuations in supply (due to weather changes). Seasonal availability of biomass leads to increased procurement costs, significant seasonal need of equipment and labour resources which lead to an inefficient supply system [162]. Diversification to several different biomass feedstocks (such as forestry residues) could be a solution but this could result in more complex logistics due to the multiple supply chains. There are additional risks during storage of fire hazards, moisture control, and health risks from fungi and spores [6].

For large scale co-firing applications, raw biomass has poor flowability, poor blending and reduces the thermal efficiency and capacity of existing boiler units [10]. Co-firing biomass with coal also has challenges that include potential increases in high temperature corrosion, ash deposition problems, pollutant emissions, increase in unburned carbon, reduced ash disposal/utilisation options and problems with deactivation of catalysts [163–166]. According to Ciolkosz [167], co-firing biomass above 30% leads to increased fouling and slagging of ash within the combustor and lower co-firing ratios have less operational problems. These technical barriers could be overcome by adapting equipment design and operation and therefore there is need for further research and testing on these aspects.

6. Conclusions and recommendations

This study has established that in South Africa, the sustainable biomass energy potential from maize and wheat residues is about 104 PJ at current conditions. There is potential to increase the amount of crop residues to 238 PJ through measures such as no till cultivation and adopting better cropping systems. In addition, there is potential to mobilise about 300 PJ from sugar cane residues, forestry residues and waste as well as municipal solid waste – which is about 10% of total coal used for power generation in South Africa.

At the farm gate, maize stover costs are estimated to 0.9–1.7 \$ GJ^{-1} while wheat straw costs between 0.9 and 1.5 \$ GJ^{-1}. In the improved scenario, about 80–85% of the biomass is available at the farm gate at cost below 1.3 \$ GJ^{-1}. For biomass deliveries at the conversion plant, about 36% can be delivered below 5 \$ GJ^{-1}. Co-firing coal and crop residues reduces total power production GHG (CO_2 eq) emissions significantly by about 0.57–0.68 t MWh^{-1} and the corresponding GHG (CO_2 eq) mitigation range from 23 to 31 \$ t^{-1}. It is also clear that co-firing biomass results in lower renewable electricity generation costs (of up to 31 \$ MWh^{-1}) compared to other renewable technologies. South Africa is already investing heavily in wind farms and solar thermal technologies, and should therefore also consider the more economic option of biomass co-firing for competitive delivery of green electricity.

This study has shown that to obtain higher volumes of crop residues, one of the key measures would be for farmers to switch from conventional tillage to no-till farming. It is clear that sustainability of residue removal is central to the long term production and supply of crop residues for energy applications. We estimate that a minimum of 2 t ha^{-1} of residues are required to reduce soil erosion to a maximum of 10% of bare soil erosion. Also varying additional amounts of residues are required to maintain healthy 2.0% SOC level. However, more analysis needs to be done to establish region specific SOC levels that would allow more accurate evaluation of sustainable residue removal rates. It would also be important to model the market dynamics of increased crop residue supply as well as cost impacts of various supply chain optimisation measures.

To establish a successful and sustainable crop residue supply system in South Africa, it is important to start by utilising the existing agricultural system to establish supply and a functional market. Once supply is established, it would be necessary to incentivise improvements and attract farmers to invest in crop residue collection equipment. To ensure biomass supply is competitive, it would also be necessary to establish pre-treatment facilities.

At national level it would important to match the infrastructure along the supply chain with the traffic demands brought by increased biomass production and supply. Moving large quantities of low density biomass requires adequate road and rail capacity to accommodate the volumes of additional commodities on the transport system. This additional burden on the transport system must be supported by sufficient investment. For long term competitiveness of crop residue supply, the rail network would have to absorb most of the traffic. Overall, more research is required to investigate various localised elements of the supply chain, including stakeholder organisation, risk assessment as well as potential technical challenges at the conversion end.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2016.06.010.

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