Biomass and Bioenergy 159 (2022) 106385

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: www.elsevier.com/locate/biombioe

The future of residue-based bioenergy for industrial use in Sub-Saharan Africa

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ARTICLE INFO

Keywords:
Bioenergy
Sub-Saharan Africa
Biomass resources
Energy demand
Sustainability
Energy transition

ABSTRACT

Energy outlooks for Africa feature increased use of fossil fuels. However, they widely ignore that a transition from traditional to modern bioenergy can support the increasing commercial energy demand and offer a high level of flexibility and dispatchability. We use energy statistics, resource assessments and demand analysis to show how switching traditional biomass use to more sustainable technologies could practically eliminate unsustainable fuelwood use. Furthermore, mobilising agricultural and forestry residue for commercial use could grow a sustainable biomass industry and offset Africa's projected expansion of fossil fuels. The assessment focuses on feedstocks and potential energy conversion options for selected and most promising bioenergy pathways in Sub-Saharan Africa's growing and economically relevant industries: cement, agricultural processing, livestock, and horticulture. Examples of specific applications are given to support the high-level resource assessment and demand balances in these sectors. Our results indicate that 3317 PJ bioenergy could be utilised in Sub-Saharan Africa. Even with the calculated gap between biomass availability and biomass demand of 5559 PJ in future energy scenarios, bioenergy can contribute to sustainable energy supply and access in SSA. The sustainability mapping highlighted that bioenergy could deliver integral social and economic impacts because of the close integration with agriculture as the main livelihood supporting sector in SSA. Sustainability frameworks and governance structures must consider bioenergy beyond its cost and clean energy potential to maximise positive trade-offs.

1. Introduction

Sub-Saharan Africa (SSA) is projected to experience rapid population and economic growth, leading to increased energy demands, particularly in urban areas (for domestic uses and mobility) and industry (for productive uses) [1–3]. Currently, affordable and sustainable energy access is inadequate. 600 million people have no electricity access; 900 million people lack clean cooking facilities [1,3]. Projections are that 530 million people will still not have adequate electricity access, and one billion people will lack clean cooking by 2030 [1,3]. Africa's current primary energy demand is about 35,000 PJ [4] and is projected to increase to 50,500 PJ by 2040 [1]. 54% of the total energy consumed in Africa is in the residential sector, 20% transport, 15% industry; 4% commercial sector and public services and 7% other sectors [4]; the non-residential uses mainly being focused on heat with only small amounts of electricity production [1]. Demand increases from productive uses and households (particularly middle- and higher income and transport) [1] are expected to drive a tripling of electricity demand in SSA. While traditional demands have focused on access to electricity and clean cooking, climate change impacts may trigger higher demands for cooling for industrial uses, households and public buildings.

Fig. 1 summarises primary energy demands in Africa. 45% of primary energy demand comes from bioenergy (~15,853 PJ) [4]. While fossil fuels are dominant in more advanced economies (e.g. in northern African countries and South Africa), bioenergy provides >80% of total energy in most SSA countries, often with agriculture-based economies [1]. Demand for biomass and waste is projected to decrease sharply to 8248 PJ until 2030 and is sustained to 8876 PJ through to 2040 [1,4]. There is some increase in renewables, but biomass reduction is predicted to be compensated by increased fossil fuel use: particularly oil and gas (most likely for projected industrial and commercial growth), which would significantly increase greenhouse gas emissions.

Biomass in the form of fuelwood and charcoal presently provides about 5653 PJ per year [5]: about one-third of the 15,853 PJ primary

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https://doi.org/10.1016/j.biombioe.2022.106385
Received 1 September 2021; Received in revised form 24 January 2022; Accepted 7 February 2022
Available online 21 February 2022

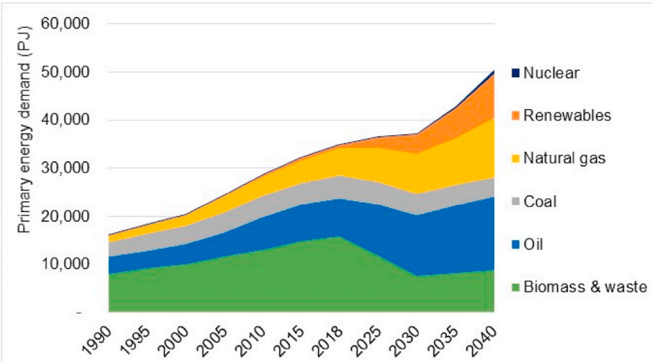

Fig. 1. Primary energy demand in Africa and projections for 2040 [1,4].

energy demand from biomass given by IEA [4]. Fuelwood and charcoal are often sourced unsustainably and used in inefficient domestic and commercial applications, resulting in significant environmental and health risks [1,6]. The unsustainable sourcing is reflected by the continuous level of deforestation in SSA. As a result, forest area and forest biomass carbon stocks reduce by about 3.9 million ha and 317 Mt carbon per year [7]. This translates into a loss of about 634 Mt biomass (dry basis) containing 11,412 PJ energy. Not all of this biomass is used for energy. Still, the current use of fuelwood and charcoal indicates that sourcing wood for fuel is a driver for reductions in forest area and carbon stocks. Therefore, a transition from traditional unsustainable biomass use to modern bioenergy approaches and sustainable renewables is urgently needed.

Detailed scientific data on present and future energy demand across Africa is lacking. E.g. a Science Direct search of publications on energy in 2020 returned 42,000 publications for Europe; 37,500 for America, 119,000 for Asia but for Africa, only 15,500 [8]. Africa is home to 34% of the current global population with the highest growth rate [1]. It is the global region with the lowest energy access whilst facing significant future challenges for sustainable and fair energy supply [1,2]. Yet only 7% of academic publications on energy investigate Africa.

Furthermore, less than 30% of those African energy publications included biomass, despite its current dominance in energy supply. Recent years showed an increase in the published literature on bioenergy in SSA. Most work focuses on either specific feedstocks, specific technologies, specific energy vectors or specific countries. This is highly important for local bioenergy development but is often limited to a disciplinary focus. Most research does not build the full link between resource availability (including mobilisation), suitability and best uses of biomass within the concept of the wider energy systems, limiting insights into the role of bioenergy for the wider energy demand of a region or end user. This makes it difficult for policy and industrial policy maker to understand the wider potential of bioenergy deployment. There is an urgent need to strategically consider how SSA transitions to more sustainable uses of biomass within the context of increasing population, economic growth and energy demand as this creates increased pressure on energy generation, infrastructure development, technology and business model innovation.

This work provides insights into how sustainable modern bioenergy can meet the current and potential future energy demand in SSA. We assessed the potential for sustainable agricultural and forestry residue and examined energy conversion options for different bioenergy pathways. This includes assessing the biomass demand impact of switching from traditional to modern bioenergy uses. The assessment focused on residues-based feedstocks to avoid land-use conflicts and draw on an existing potential of biomass that often is not utilised and disposed of unsustainably. Purpose-grown energy crops can provide and increase the potential and open additional avenues for modern bioenergy. However, the scope of the study was to understand the existing biomass residue potential. We recognise that biomass availability is highly variable across regions and that bioenergy supply chains and business models cannot be easily replicated in different locations.

We developed mass-energy balances to generate technical performance data for the selected commercial applications to evaluate how biomass supply can meet the energy demand. We focused on three industrial sectors that are particularly relevant to SSA economies with future growth potential as economies industrialise: cement production, agricultural processing, and livestock and horticulture. In assessing cement and agricultural production, biomass was used to investigate an energy demand during industrial processing. In the livestock and horticultural sector, the mass-energy balance much more represented an energy potential when utilising instead of disposing of organic waste streams.

A multi-criteria sustainability assessment provided insights on wider sustainability impacts and trade-offs of the three investigated industrial sectors compared to traditional biomass use, illustrating the potential impact of modern bioenergy deployment. Finally, we used the results from the assessments to develop a possible vision for a more sustainable bioenergy future for SSA that enables energy innovation and Sustainable Development Goal (SDG) benefits for commercial bioenergy applications in SSA. This quantitative vision can guide strategies and governance frameworks to support clean, fair and sustainable energy solutions delivering against SDGs.

The work was completed as part of the Bioenergy for Sustainable local energy services and Energy Access in Africa (BSEAA) project and (in line with the wider project objectives) focused on commercial deployment and the need for energy innovation strategies in SSA.

2. Methods

Fig. 2 presents the methodological approach for the assessment of this study. The resource and energy demand assessment provides insights into biomass availability, mobilisation, technical feasibility and energy potential. Finally, the sustainability mapping synthesises the results and supports a better understanding of the benefits and impacts of biomass use within the investigated sectors.

2.1. *Resource assessment*

Previous work shows a large biomass potential for SSA, but significant variability: (10,000–24,500 PJ for 2050 [9,10], driven by different assessment frameworks, approaches and assumptions, compounded with uncertainty related to yields, mobilisation and land-use decisions [10,11].

Our biomass resource assessment aimed to conservatively quantify the biomass feedstock and energy potential from residues only, with no additional land-use, land-use change or competition with food production (see Supplementary Material S1 and Tables S2–4). This “low-risk” approach avoids land-use conflict and related sustainability issues but conversely delivers lower levels of tangible benefits for stakeholders, e.g. direct planting of energy crops might deliver more economic development and soil remediation opportunities that will be missed via this more restrictive assessment.

The resource assessment was based on agricultural and forest production and processing data from the FAOSTAT database [5] using data from the year 2018. The resource assessment has been developed at a national level using country-specific data. This was then aggregated to provide a high-level estimation of the residual biomass in SSA. The complete list of countries and crops included in the assessment is provided in the Supplementary Material S1. While it is recognized that context-specific assessment can invariably improve definition and accuracy or deployable resource, the current methodology provides a robust assessment of potential.

The assessment did not include any potential from municipal waste streams. This sector is not well developed in most SSA countries, and

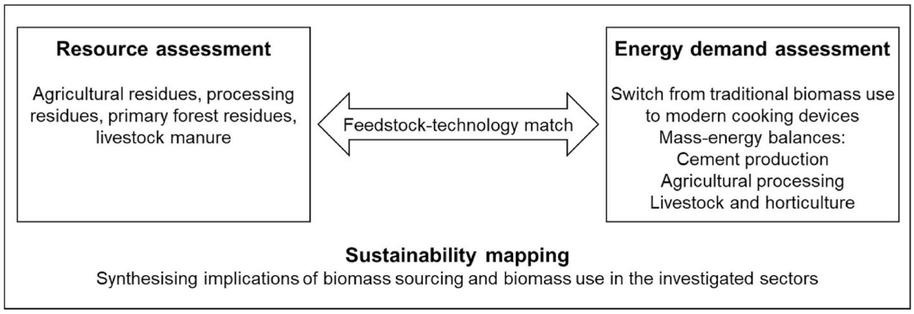

Fig. 2. Methodological approach assessing residue-based bioenergy potential for industrial use in Sub-Saharan Africa.

data is limited. However, it is recognized that this could be a very significant resource moving forward, particularly with population and urbanisation projections. The following feedstock categories were considered [12] (see more detail Supplementary Material S1):

- Primary agricultural residues (comprising primary residues from agriculture that occur during crop management or post-harvest, e.g., straw, stalks, stover, leaves and small branches)
- Agricultural and forest processing residues (comprising residues generated during the industrial processing of agricultural and wood products, e.g. husks, peels, stones, fibre, bagasse and sawdust, off-cut and wood chips from wood processing
- Livestock manure (comprising manure and slurries from stalled livestock)
- Primary forest residues (comprise small trees from thinnings, branches and low-quality wood)

The residual biomass potential was calculated based on the amounts of crops produced, processed, or livestock reared, the residue-to-product ratio, the recoverable fraction and the fraction of biomass available after considering other uses. The return of nutrients and organic matter to soils were included in the assessment and described for each feedstock category in detail in the Supplementary Material S1. Finally, the theoretical energy potential was calculated considering the available residual biomass and the energy content of the biomass on a dry basis (d.b.). The detailed methodology and data are provided in the Supplementary Material S1, Tables S2 and S3.

The resource assessment considers current agricultural and agri-processing practices; hence the calculations of crop and livestock residues are based on current crop production levels and how livestock is kept. Therefore, improvements in crop yields could lead to higher residues rates, but experience has shown the challenges of improving crop yields in SSA, which is also linked to the smallholder character of SSA. Enhancing crop yields is not just a technical question but needs careful consideration of broader agri-social aspects of SSA farming systems and how changes in practices and technology innovations affect small-hold farmers.

Due to a lack of data, the resource assessment of primary and processing residues did not include a quantitative factor for infrastructure development and scale, as we included for livestock residues. The real potential of crop residues could be much lower due to barriers for mobilisation, such as the cost of collection and transport and limited infrastructure.

2.2. Energy demand assessment

In SSA, over 90% of the current primary energy demand from biomass of 15,853 PJ is related to traditional biomass use in the residential sector [1] (e.g. cooking) and using applications with low conversion efficiencies, of typically 10% [13]. We assessed the reduction of biomass use by switching domestic cooking to technologies with improved efficiency and using biomass that does not contribute to deforestation, require planting or dedicated land-take. We calculated the revised energy demand by switching to an ethanol stove, with typically 75% energy conversion efficiency [14], and considered the need to produce ethanol from biomass with associated conversion losses of 45% [15]. This switch would stop unsustainable fuelwood use but result in a need for biomass with high sugar content to produce ethanol. The assumptions and conversion factors for switching from traditional to modern bioenergy are presented in Table 2.

Bioenergy offers an extensive array of feedstock, technology and application choices. The assessment focused on bioenergy pathways with commercially-available technologies, as project stakeholders perceived these as more viable in the current commercial, technological and policy context of SSA. This does not mean novel technologies at currently low technology readiness level would not be feasible for the SSA context, but the right commercial and policy framework would need to exist.

We considered the potential for deploying modern bioenergy in commercial sectors to support industrial and commercial growth with reduced unsustainable energy sources. We focused on three key sectors that are particularly relevant to SSA economies with future growth potential as economies industrialise [16]:

- Cement production, driven by high rates of urbanisation and increasing development of housing and infrastructure
- Agricultural processing like tea, palm oil, sugar and sisal as growing and value-added export sectors and with livelihood benefits from improved income and employment
- Livestock and horticulture as the consumption of meat and dairy products and marketed and processed vegetables and fruits strongly increases with urbanisation and economic growth

A mass-energy balance (MEB) model [17] was used to investigate commercially viable opportunities of modern bioenergy technologies for electricity and/or heat generation in the output range 10 kWe to 5 MWe [18] from regional feedstocks (see Table 1 for more detail see Supplementary Material S2). Typical plant configurations matched to the feedstock and energy demand were modelled. The detailed methodology of the MEB model is described by Chong et al. [17]. The investigated sectors are shown in Table 1. Further detail of the chosen pathways discussed in this paper is given in the Supplementary Material S2 and Table S5, containing references and justification for key technical assumptions.

The MEB model is available online and can evaluate various feedstocks, scales and demands; these particular choices are made to illustrate potential [17].

2.3. Sustainability mapping

A sustainability assessment was conducted to map and synthesis the sustainability implications of biomass sourcing and biomass use in the

Table 1
Investigated commercial sectors for modern bioenergy applications in Sub-Saharan Africa.

Commercial sector	Biomass resource	Conversion technology	Scale
Cement production	Maize stalks, palm oil processing residues (e.g. kernel shells, fibre, empty fruit bunches)	50% co-firing in existing fossil fuel-fired kiln	>5 MW (Large-scale industrial processing)
Agricultural processing	Cassava stalks, rice husk, wood processing residues	Steam turbine-based CHP	10 kW to 5 MW (tea, sisal, sugar, palm oil, timber)
Livestock production, horticulture	Cow manure & rice straw, chicken manure & rice husks, vegetable & fruit residues	Anaerobic digestion producing biogas used in CHP	10 kW to 5 MW (commercial dairy production, marketed and processed vegetables and fruits)

investigated sectors. This included environmental, economic and societal impacts and associated trade-offs relevant to energy innovation and SDGs for commercial bioenergy applications in SSA.

The 'Bioenergy Sustainability Indicator Model' (BSIM) was used for the sustainability mapping [19]. The BSIM, developed by the Supergen Bioenergy Hub, uses a multi-criteria assessment framework to identify and analyse bioenergy pathways' sustainability benefits and risks and maps the trade-offs between different sustainability indicators. The sustainability indicators included in this assessment (from the >100 options in the model) were community participation & empowerment, energy access, infrastructure requirements, feedstock mobilisation, technology efficiencies, techno-economics, economic stimulation, energy system dependence, bioenergy complementing other sectors, life cycle emissions, counterfactual impacts, replacement of fossil fuels. While many other indicators are relevant for a comprehensive sustainability assessment, the relevance of indicators will vary for different bioenergy applications. For this study, the investigated indicators were selected through stakeholder engagement and discussion with project partners to address sustainability topics relevant to policy and industry decisions. Additionally, the assessment included only indicators where robust background knowledge and project- and context-specific evidence existed to avoid data input with high uncertainties or limited evidence into the model. Nevertheless, the selected indicators provide a robust high-level assessment of aspects closely related to the UN SDGs.

3. Results

3.1. Resource assessment

Fig. 3 presents the results of the resource assessment. 184 Mt residual biomass with an embedded energy content of 3317 PJ could be mobilised per year in SSA: 124 Mt (2239 PJ) from primary agricultural residues; 23 Mt (411 PJ) from processing residues; 4 Mt (73 PJ) from wood processing residues; 16 Mt (293 PJ) from livestock residues and 17 Mt (300 PJ) from primary forest residues (all dry basis).

Primary agricultural residues provide the largest biomass potential, with the major share coming from staple crops like maize, cassava and cereals, including sorghum and rice. These residues are plentiful due to large production and a high residue-to-product ratio. They have a high dry matter content (~50%–85%), making them suitable for thermal conversion like combustion and gasification but less suitable for biological processes like AD.

The availability of residues from other produce categories, such as pulses, roots and tubers, nuts, oilseeds and vegetables, are significantly lower due to the scale of crop production. In addition, these often have a high moisture content, so would be more suitable for AD or require drying before thermal conversion.

Livestock slurries and manures provide a high bioenergy potential. They are potent AD feedstocks, and digestate is a valuable replacement of slurries and manure as fertiliser. However, the use of livestock slurries and manures are often only feasible if livestock is kept in settings like stalls or pens, where the manure can be easily collected.

Primary forest residues have a potential of 300 PJ (17 Mt). Currently, fuelwood and charcoal are the main solid biofuels in SSA (~5653 PJ) [5] and are generally sourced and used unsustainably. Although the removal of primary forest residues like branches and low-quality wood can improve forest management, sustainable business models can support increasing forest carbon stocks [20], the level of transparent and sustainable forest management is currently very low in SSA [7]. Therefore, the assessment included potential from forests with long-term management plans and planted forests only and excluded any protected areas. While these two forest management categories do not eliminate all uncertainties of unsustainable practices, they offer some

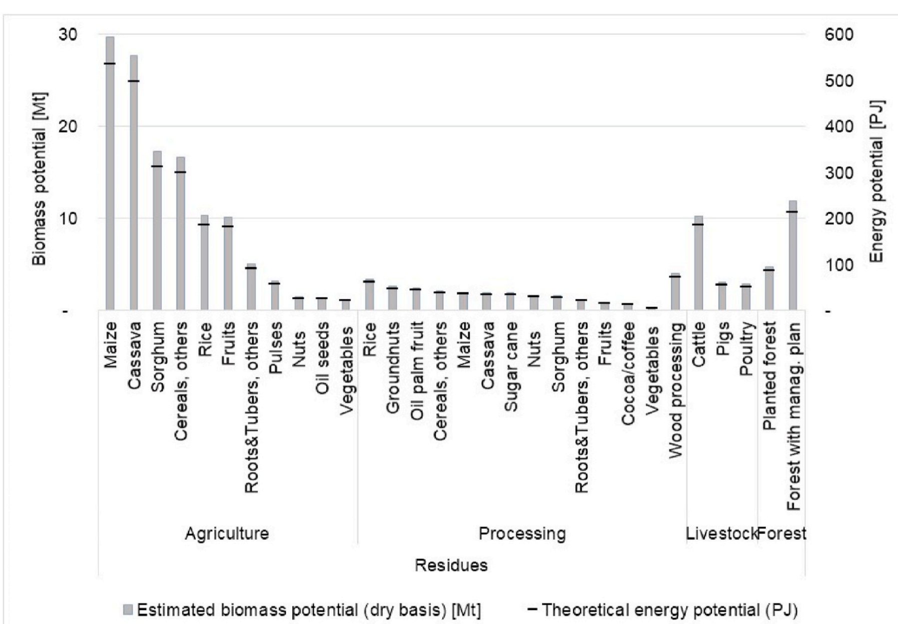

Fig. 3. Annual biomass resource and bioenergy potential from different residue categories and sources in Sub-Saharan Africa.

level of transparency or traceability.

3.2. Energy demand assessment

Table 2 summarises the primary bioenergy demand reduction achieved by switching from traditional biomass cooking devices to well-established ethanol cookstoves for two baseline demand assessments: based on IEA energy statistics and the current reported fuelwood and charcoal production. Through this switch, the demand for biomass decreases by 76% to 3843 PJ in the former scenario and 1371 PJ in the latter.

The switch is achieved by accessing biomass rich in sugars or starches instead of lignocellulosic fuelwood. Hence, this cannot be considered a direct displacement of biomass but rather a fuelwood saving of 15,853 PJ (or 5653 PJ) and a new demand for biomass-to-ethanol feedstock of 3843 PJ (or 1371 PJ). Theoretically, the fuelwood saving could become available for other uses, but given concerns over existing unsustainable sourcing/deforestation, it was conservatively credited as a reduction in unsustainable biomass sourcing and not reallocated.

Table 3 presents the mass-energy balance results for the deployment of modern bioenergy in the three investigated commercial sectors.

- In cement production, 63,797 t palm oil residues or 71,772 t of maize residues (all dry basis) are required to replace 50% of the fossil fuel demand to produce 1 Mt of cement. If all palm oil residues or maize residues replace 50% of fossil fuels in cement production, 39 Mt or 414 Mt cement could be produced.
- For agricultural processing, using a thermal application with a steam turbine-based CHP would require 1892 t to 10,722 t of cassava stalks, 1670 t to 9461 t of rice husk or 1682 t to 9531 t of wood processing residues per year to operate a 1 MWe at 85% plant availability and depending on the final energy vector demand.
- An AD facility with a biogas CHP would require 22,684 t to 26,274 t of mixed livestock manure-crop residue feedstock or 21,122 t of vegetable and fruit waste per year to operate a 1 MWe facility at 85% plant availability.

Variation within these ranges is driven by assumptions on electricity-to-heat ratio, conversion efficiency (linked to plant specification/design) and plant availability. However, these results give a high-level indication of annual feedstock requirements and the extent to which industrial development can be supported by agri-residue mobilisation.

3.3. Sustainability mapping

The results from the sustainability mapping are presented in Fig. 4, with each line representing one of the three investigated sectors and the current status of traditional biomass use. As the results are a sum of the benefit and risk, a positive value presents a benefit outweighing the risk versus a negative value where the risk outweighs the benefit for the sustainability indicator.

The bioenergy application in the three investigated sectors is more beneficial and sustainable than traditional biomass use, apart from techno-economic cost, showing that current market conditions do not support the change. Overall, there are some variations in benefits and risks comparing the three sectors. Still, similar impacts and trade-offs can be observed for the different indicators. The most pronounced differences are for replacing fossil fuels as cement production only substitutes 50% of fuel with sustainable biomass, while agricultural processing and livestock and horticulture replace all fossil fuel and unsustainable biomass. The other significant difference between the different sectors is for feedstock mobilisation. Cement production and agricultural processing are likely to depend on feedstocks in dispersed remote locations with associated risks for mobilisation (availability, cost, infrastructure). On the other hand, AD systems often draw on existing waste streams that can be easier mobilised with advantages in utilising waste that would otherwise create a significant disposal issue and generate substantial environmental risks.

Six out of the ten assessed indicators pose a greater benefit than risk for all three commercial sectors. The indicators are replacement of fossil fuels, economic stimulation, energy access, participation & empowerment, lifecycle emissions and indoor smoke. Conversely, the risk outweighs the benefits for at least one of the sectors for the remaining indicators (feedstock mobilisation and infrastructure requirements). For technology efficiency and techno-economics, all three commercial sectors indicated some risk, as there is always a risk associated with an investment in advanced technology. However, even with some indicators showing higher risks than benefits, overall bioenergy integration into the commercial sectors is beneficial. The benefits scores were significantly higher (highest benefit score: 8.5) than the scoring of the risks (highest risk score: 2.7), highlighting the positive sustainability outcome.

Depending on the drivers for bioenergy, the sustainability indicators will be weighted and valued differently. For example, suppose greenhouse gas emissions and environmental performance (SDG13) are the main drivers. In that case, the two smaller-scale applications can be highly beneficial, offering benefits from counterfactual impacts. From a total carbon budget perspective, cement as a hard to decarbonise sector will also benefit from biomass use, translating into a low carbon built environment.

Supporting energy access and energy resilience (SDG7), the two CHP systems appear more beneficial than cement production. They can support energy demand beyond the actual energy generation if surplus energy is distributed, but this critically requires a local energy demand, which is context/location-specific. Moreover, there can be indirect benefits if stakeholders access services provided by the bioenergy application, e.g., processing crops and produce (e.g. drying, milling, support local processing or retail) that adds value to their products. Such direct and indirect benefits are usually unavailable in large-scale facilities where biomass is used directly with no energy outlet. Large-scale applications with varying demands of energy and processing steps could support wider energy access if an energy outlet is available (e.g. sugar processing, pulp and paper). Still, the two CHP pathways are more likely to support community participation and empowerment as a co-benefit.

Large-scale applications have a competitive economic advantage through economies of scale and utilising existing infrastructure. While investments might be high for a smaller scale, there can be higher non-monetised benefits from such applications by supporting sustainable self-supply, supporting income and employment, adding value and participation of a significant number of stakeholders.

Table 2
Reduction in biomass demand for clean cooking by technology switching.

	Primary bioenergy demand (IEA [4])	Fuelwood and charcoal use (FAO [5])
Current primary energy demand for cooking using traditional biomass stove	15,853 PJ	5653 PJ
Cookstove efficiency [13]	10%	10%
Actual cooking energy supply	1585 PJ	565 PJ
Efficiency of heat provision from ethanol stove [15]	55%	55%
Projected ethanol demand for modern cookstove	2882 PJ	1028 PJ
Efficiency of conversion of biomass feedstock to ethanol [14]	75%	75%
Projected demand for biomass feedstock	3843 PJ	1371 PJ

Table 3
Results mass-energy balance and bioenergy potential of commercial sectors.

Feedstocks	Biomass input (dry basis) (t)	Biogas production (Nm^3)	Product/energy output	Losses (MW)	SSA Biomass potential Feedstock (Mt)	SSA product/energy output potential	SSA energy output potential (PJ)
Cement production							
Maize stalks, cobs	71,772	n/a	1 Mt cement	n/a	30	414 Mt	n/a
Palm oil processing residues	63,797	n/a	1 Mt cement	n/a	3	39 Mt	n/a
Steam-turbine CHP heat generation							
Cassava stalks	1892	n/a	1 MWth	0.2	28	14,635 MWth	392
Rice husk	1670	n/a	1 MWth	0.2	3	2027 MWth	54
Wood processing residues	1682	n/a	1 MWth	0.2	8	4813 MWth	129
Steam-turbine CHP electricity generation							
Cassava stalks	5361	n/a	1 MWe	2.3	28	5165 MWe	138
Rice husk	4730	n/a	1 MWe	2.3	3	716 MWe	19
Wood residues	4765	n/a	1 MWe	2.3	8	1699 MWe	46
Steam-turbine CHP heat and electricity generation							
Cassava stalks	10,722	n/a	1 MWe & 4.3 MWth	1.3	28	2582 MWe & 11,105 MWth	367
Rice husk	9461	n/a	1 MWe & 4.3 MWth	1.3	3	358 MWe & 1539 MWth	51
Wood residues	9531	n/a	1 MWe & 4.3 MWth	1.3	8	849 MWe & 3652 MWth	121
Anaerobic digestion CHP							
Cow slurry & Rice straw	22,684	10,237,039	1 MWe & 4.3 MWth	1.3	21	912 MWe & 3921 MWth	130
Chicken manure & Rice husk	26,274	10,752,850	1 MWe & 4.3 MWth	1.3	6	238 MWe & 1023 MWth	34
Vegetable waste & Fruit waste	21,122	10,028,316	1 MWe & 4.3 MWth	1.3	1	56 MWe & 239 MWth	8

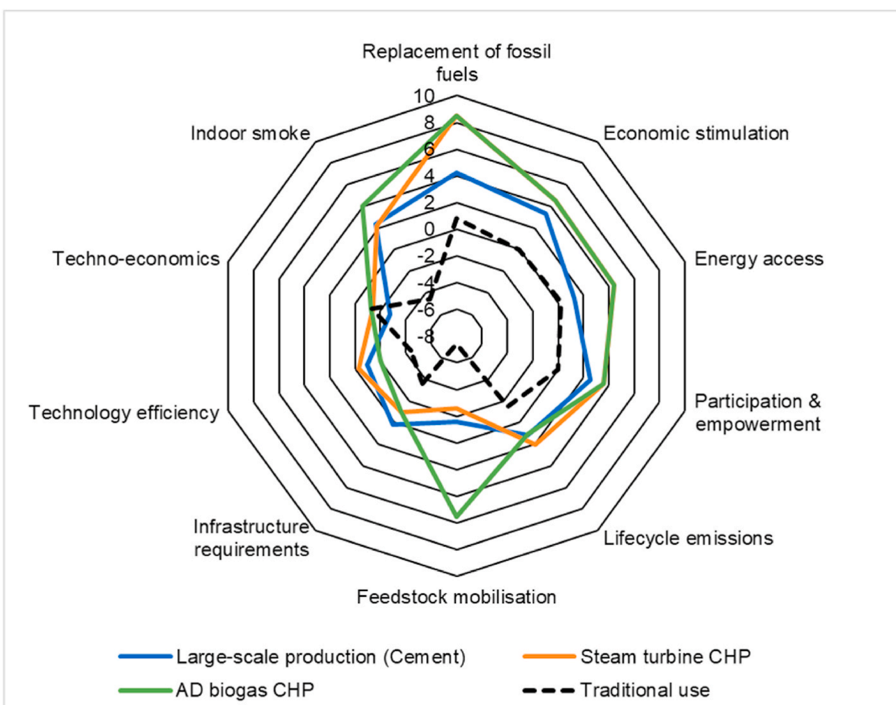

Fig. 4. Sustainability mapping of three bioenergy sectors and traditional bioenergy, presenting trade-offs between benefit and risk.

4. Discussion

The resource assessment estimated a biomass potential of about 184 Mt (d b.), providing 3317 PJ of energy. Our estimates for primary and processing resources of about 2650 PJ are within the same order as other studies, with ranges between 1089 PJ to 3588 PJ [10]. Our results for wood processing residues (73 PJ) are at the lower end of the up to 356 PJ potential calculated by others [10]. We allocated a 40% share of these residues to existing uses in sawmills for internal processes, and less would be available for other bioenergy applications, limiting our calculated potential.

Similarly, the results for livestock waste (293 PJ) are lower than results from other studies (28 PJ to 1450 PJ) [10]. Many studies consider the potential of the total livestock herd in SSA. Our assumptions are based on manures arising in settings that allow the collection and support a feasible deployment scale. Livestock operations often need to be at a commercial or community scale to be feasible for manure collection and AD [21]. This excludes the largest share of ruminate livestock in SSA, kept in small-scale, pasture-based and extensive rearing [5]. Manures from non-commercial and extensive livestock systems could provide the potential for small scale bioenergy applications; however, these are outside the scope of our study. Commercial livestock systems become more apparent with increasing urbanisation and economic growth, especially for the dairy and poultry sectors [22–24]. This could further increase the bioenergy potential from livestock waste in the future.

About 80% of farms in SSA are small-scale, where crops are grown on remote fields, with low yields and in small amounts [25]. Similarly, small-scale processing still dominates the agri-processing sector in SSA [25,26]. This means that the agricultural residues mainly occur in remote areas, are scattered and are only available in small amounts. The availability can be further restricted by seasonal availability. This and related cost, time and labour for collection can make mobilisation and utilisation difficult [27,28]. Therefore, assessing the context and location-specific business models would be necessary to understand projects' economic feasibility and profitability.

However, in small-scale processing, residues are more likely to accumulate in one place, reducing mobilisation challenges if adequate amounts and quality of processing residues are generated to meet the energy demand of processing and commercial uses. In that case, bioenergy can offer an integrated solution supporting energy demand from an occurring waste stream. For example, cereal mills can use husks for drying, palm oil and groundnut mills can use solid residues for thermal application to produce process heat, fruit and vegetable markets or processors can use residues and spoiled produce in AD to produce heat or electricity for processing and cooling.

Where biomass supply and energy demand occur in different locations, inadequate infrastructures can limit the economic and technical feasibility for medium- or small-scale applications. However, community-based applications have the advantage of being more flexible by tapping into arising biomass resource streams and supporting community participation and energy access.

Established large-scale industries often have well-developed infrastructures, supply chains and business models. As a result, they can use existing structures, assets, knowledge and technology of scale to integrate biomass use. Still, where feedstocks are sourced in small batches from many small-scale providers, the quality and consistency of biomass supply can vary widely. This can reduce the technical efficiency and operational performance of the bioenergy facility.

Local hubs collecting biomass or local modular bioenergy applications within close proximity to the location of the residue could help overcome some mobilisation barriers. Moreover, robust technologies that can utilise different types of feedstock or use biomass of varying quality can help address some of the challenges of consistency of supply, seasonality and quality.

The mass-energy balances provided an insight into the biomass requirements that can match commercial energy demand with potential sectoral growth and where bioenergy integration is feasible or is already happening. SSA countries are currently producing 95 Mt of cement per year [29]. The results demonstrate that palm oil residues, which are currently used by some plants [30], would not be sufficient to replace 50% of fossil fuel in all cement production. Compared to this, primary agricultural residues, like maize stalks, are plentiful and could support an even higher level of fossil fuel replacement. The SSA tea sector produces about 700 thousand tonnes of made tea per year [5], with an energy demand of 19 GJ/t of made tea [31]. As our assessment demonstrates, a targeted energy capacity of about 422 MW is required, which can be well covered by available biomass resources.

In livestock production, the typical energy demand for dairy cows varies between 365 kWh and 1200 kWh [32,33], depending on the management systems and climatic regions. Suppose dairy cows in a modern indoor livestock system in SSA require about 1200 kWh per year. A targeted capacity of 0.14 kW is required per cow. For the resource assessment, we assumed that about 2% [34] of the total cattle herd of about 343 million cattle in SSA [5] is managed in commercial settings requiring this level of energy supply. This results in a target capacity of about 940 MW. Based on this, the dairy sector could only have a self-sufficient energy supply if manures collected on-site are mixed with additional, in our case, crop-based feedstocks.

The assessment showed variations in biomass demand and energy potential from biomass. The variations reflect the impact of differing feedstock compositions, plant operations and performance. Such variations can significantly affect supply chain performance in terms of energy, price, transport, storage, handling and are particularly important when facilities mix different biomass. Therefore, understanding efficiencies and related energy outputs are equally important. Plant operators and supply chain actors need to take a complete system overview rather than focusing on a single performance metric.

Overall, available biomass offers a significant energy potential for the investigated sectors. While theoretical assessments can provide an insight into biomass input and energy output, real-life operational and practical aspects need to consider how biomass supply and energy demand can be met. It is crucial to understand how much, what type and when biomass is required, as spatial and seasonal availability of biomass will not necessarily correspond to the energy demand. The disperse and seasonal availability of biomass might need business models that include using different feedstocks at different times of the year depending on availability and how this matches the energy demand for industrial processes that might have peak seasons or peak times (e.g., processing of seasonal produce, energy demand at specific times of a day, like lighting in livestock sheds or buildings).

The energy outlooks for Africa [1,3] project an increasing demand for fossil fuels, especially for productive uses. Our assessment provides an insight into the biomass potential, but increased bioenergy deployment in emerging and growing commercial sectors would lead to increased competition for biomass [35,36]. Therefore, a demand-side approach estimating the demand of modern applications is required to fully understand what contribution bioenergy can make in terms of energy supply, where it is a feasible option compared to other renewables and, in particular, where it can replace fossil fuels avoiding greenhouse gas emissions.

The residential sector is currently the main sector using bioenergy. The assessment showed the potential of switching traditional fuelwood use to more efficient energy provisions. This could offset some of the deforestation currently experienced in SSA and reduce primary energy demand on a household level. Still, fuel for domestic uses is needed even with the technology switch, and demand is likely to increase with economic growth and urbanisation. If fossil-derived fuels are used in stoves as suggested by some energy outlooks [3], the greenhouse gas mitigation achieved would be significantly less. Moreover, our suggested technology switch would not free up sustainable biomass resources for commercial uses. As for the residential sector, small technology and operational improvements could reduce the demand for biomass or increase the energy output in the commercial sector significantly. To achieve this, there is an urgent need to deploy modern energy technologies and improve technical and operational performance of existing facilities.

Nevertheless, our assessment showed that the calculated sustainable bioenergy potential of 3317 PJ falls far short of the current 15,853 PJ and projected 2040 primary bioenergy demand of 8876 PJ [1]. This is also significantly lower than the energy currently provided from fuelwood and charcoal (~5653 PJ), but the technology switch showed that this demand could be reduced considerably. Still, a gap between our resource assessment and energy demand projects exists, partly explained by the conservative low-risk assumptions taken for this assessment.

Our resource assessment showed a biomass potential from residues from managed forests and plantations of about 300 PJ. However, this potential can be significantly increased if long-term forest management plans and minimum sustainability benchmarks are introduced, simultaneously reducing the risk of unregulated logging and deforestation. Currently, SSA has about 312 million ha of naturally regenerated forest, after excluding primary forest and protected areas [5,7]. These forests could provide additional primary forest residues from management activities by adapting sustainable forest management practices. For example, in 30-year forest growth rotations with a mean annual increment of 20 m^3 [37], these areas could provide an additional 2812 PJ of sustainable biomass. Mobilising this potential can be challenging, and it would require thorough and transparent sustainability monitoring as currently high levels of unsustainable deforestation can be observed in SSA [38]. However, long-term forest management plans and minimum sustainability measures would diminish opportunities for unregulated logging. Additionally, a technology switch from traditional to modern energy applications would be imperative as it would otherwise undermine energy access for households.

It must be acknowledged that future scenarios are likely to consider bioenergy feedstocks not included in this assessment, like purpose-grown energy crops, short rotation coppice/forest and municipal waste streams (municipal solid waste, wastewater and sludges). Others have shown that purpose-grown biomass could provide a recognisable potential [39]. However, values range significantly and only offer meaningful potential where future policies introduce dedicated bioenergy strategies [10,39]. With increasing urbanisation, municipal waste management and wastewater treatment may become more implemented in SSA, which would offer additional energy potential.

Even with the calculated gap between biomass availability and biomass demand in future scenarios of 5559 PJ, bioenergy can contribute to sustainable energy supply and access in SSA. Compared to other renewable energies, bioenergy can deliver integral social and economic impacts much more directly than other energy systems because of the close integration of agriculture as the main livelihood supporting sector for most SSA population. This offers immense potential for economic stimulus and community benefits. Sustainability frameworks and governance structures must consider bioenergy beyond its clean energy potential of the sustainable development goals SDG7 and SDG13 to maximise positive trade-offs.

Despite technical and economic challenges of mobilising biomass from small-scale agriculture, deploying technologies and business models that allow community level participation can empower supply chain actors and create more long-term upstream and operational jobs than other renewable technologies that are often imported from remote factories and only stimulate local economies during construction. While large-scale industries like cement production can offer participation for small-scale feedstock providers, employment, skill development, such operations often do not provide the level of community participation and decision making for a wider group of stakeholders. Compared to this, community-based applications can provide considerable direct benefits for economic stimulation through income generation and skill development within bioenergy supply chains, improved energy access and avoided energy cost through self-supply at the community level beyond generating revenue from energy provision.

If generating energy surplus, community-based systems can support off-grid energy access in remote communities, benefiting productive and household energy use. The mass-energy balance calculation showed that CHP systems could maximise energy production and could potentially offer additional energy services to the community beyond commercial self-supply. This could be another way of addressing the technology switch from traditional to modern bioenergy use for commercial and residential energy use.

Modern bioenergy applications are usually more expensive than conventional fuels or other renewables. A focus on the cost of energy can easily lead to missed opportunities for net positive impacts. Bioenergy systems are engineered processes designed to deliver a particular need. Therefore, they are connected with higher skills during operation than other technologies, such as solar panels, wind or hydro-electric turbines. Even within existing sectors, as the ones investigated, this can create new jobs and income.

Because of the close link to livelihoods, potential benefits and risks need to be taken into account, and it must be recognized that the results are not automatically transferable. While our assessment took a high-level view, decision-makers need to look more closely at the country, if not the location level. This will provide a more detailed picture of biomass availability and energy demand. Only this will ensure an appropriate assessment of the sustainability indicators in the context of the actual practices implemented for different bioenergy pathways, including policy support and investment opportunities.

5. Conclusion

Our research showed that bioenergy could significantly contribute to energy provision in SSA. However, a transition to sustainable biomass use, efficient technologies and good operational practices are needed. Converting existing unsustainable fuelwood use to modern bioenergy technologies would reduce deforestation and utilise currently underutilised biomass resources. Even with the calculated gap between biomass availability and biomass demand in future energy scenarios, bioenergy for productive uses could adequately be met. The industrial use of bioenergy can offset some of the projected expansion of fossil fuels in SSA. While bioenergy is likely to require higher investments than other renewable energy sources, it offers opportunities for net positive impacts and unique co-benefits and non-monetised values. The close integration with agriculture as the main livelihood supporting sector in SSA supports economic stimulus and community benefits beyond its clean energy potential of the sustainable development goals SDG7 and SDG13. Considering these trade-offs should be part of informed decision making about bioenergy interventions. To maximise these sustainability benefits, local stakeholders and communities need to be included in business model design and decision making and be given opportunities to participate in supply chain activities. This will then allow to transfer knowledge and share experience from the perspective of beneficiaries and participating actors and fertilise South-to-South collaboration rather than North-to-South implementation.

Acknowledgements

This research has been conducted as part of the 'Bioenergy for Sustainable Local Energy Services and Energy Access in Africa - Phase 2' (BSEAA2) project and was funded by the UK Foreign, Commonwealth and Development Office (FCDO) as part of the Transforming Energy Access programme. The views expressed do not necessarily reflect the FCDO's official policies.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2022.106385.

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