TITLE

"A systems approach to risk and resilience analysis in the woody-biomass sector: A case study of the failure of the South African wood pellet industry"

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ABSTRACT [1]

Currently more than 600 million of the 800 million people in SSA are without electricity, and it is estimated that an additional 2500GW of power is required by 2030. Although the woody-biomass market in the developed world is relatively mature, only four woody-biomass plants in SSA have been established, all of which were closed by 2013. With its affordable labour, favourable climate and well-established forestry and agricultural sectors, South Africa appears to have the potential for a successful woody-biomass industry. This paper documents a first attempt at analysing why these plants failed. It aims to contextualise the potential role of a sustainable woody-biomass sector in South Africa, through firstly developing a SES-based analytical framework and secondly, using this to undertake a retrospective resilience-based risk assessment of the four former woody-biomass pellet plants in order to identify strategies for increasing the resilience of the industry. The SES-based framework advances previous theory,

[1] European Union (EU), Natural resource-based enterprises (NRBEs), Social-ecological system (SES), Sub-Saharan Africa (SSA), United Kingdom (UK), United States (US)

which usually focuses on natural resources and their supply, by introducing a production process (with inputs and outputs), internal business dynamics and ecological variable interactions. The risk assessment can be used at a broad level to highlight important aspects which should be considered during feasibility assessments for new plants. Further work is proposed to focus on splitting the social-ecological system at different scales for further analysis, and to investigate the long-term ecological impacts of woody-biomass utilisation.

HIGHLIGHTS

- Applying and extending SES theory in relation to the woody-biomass sector generated beneficial insights, especially at a landscape level
- The proposed risk assessment approach can identify the key aspects which should be considered when establishing a new plant
- There is a need for further investigation into the long-term ecological risks under South African conditions
- Local market development should be pursued as it will address many economic risks associated with the industry

KEY WORDS

South Africa, woody-biomass, social-ecological system, resilience, risk, framework

1. INTRODUCTION

1.1 Background

Energy provision in Sub-Saharan Africa (SSA) is fundamental to growth and diversification of industry and therefore economic development. Currently more than 600 million out of 800 million people in this region are without electricity, and it is estimated that an additional 2500GW of power is required by 2030 [1]. The greatest proportion of power demand comes from South Africa [2] and demand is planned to be met by a mix of renewable and non-renewable solutions.

In the northern hemisphere, legislation promotes substitution of fossil fuels with renewables (e.g. the EU Renewable Energy Directive [3], the US Energy Policy Act 2005 and US Energy Independent and Security Act of 2007 [4]). However, although work on renewable policy has been undertaken in South Africa [5, 6, 7], no similar legislation has been forthcoming [8]. Although wind, solar and hydropower have been implemented in some areas in South Africa, their main limitation is dependence on weather conditions [9], most notably limiting industrial applications [10]. Biomass is the only renewable source of energy which is not weather-dependent, and has acknowledged additional ecological, social and economic benefits (refer to **Supplement 1 in supplementary material**). Despite woody-biomass being the most utilised source of energy across the globe [11], negative connotations in SSA persist, considered by some as an energy which 'engenders poverty', 'comes from the past', is 'dirty', 'inefficient' and a 'subsistence fuel' [12]. Contradictions between the significance of biomass for countries in SSA and the low profile it is given in national policies are noted [13], where it is argued that biomass energy initiatives are ignored by decision-makers who consider economic growth and poverty reduction dependent on continued use of fossil fuel. Despite job creation being a priority in SSA and that woody-biomass production has the potential to create two to three times [14], and even to up to 20 times [15] more jobs compared to coal production, policy-makers in SSA are still dismissive of biomass.

Woody-biomass is derived from a variety of sources (e.g. plantation and sawmilling operations, alien plant removal). Pelletisation prior to application is favoured over direct combustion as it has a higher calorific value [11], less harmful emissions (<1% compared to ca. 65%) [16], creates greater job opportunities [17] and is more logistically favourable [18]. A simplified flow diagram of the pellet supply chain is presented in **Figure 1.**

Figure 1. Woody-biomass production process

In many parts of Europe, South America and the US, biomass pellet use is increasing rapidly in domestic, commercial and industrial sectors supplying electricity, heat (e.g. domestic stoves [19], bakery ovens [20]), combined heat and power (CHP), and fuel for transportation [21]. Co-generation applications, where some coal is substituted with pellets, are also increasing rapidly in the US, Finland, Denmark, Germany and Belgium [15]. In Europe alone, wood fuel production increased from 125hm^3 in 2001 to nearly 160hm^3 in 2011 [22], and ca. 4.4Mt of wood-pellets were imported across European Union (EU) borders in 2012 [23]. The European biomass sector has developed in response to the EU Renewable Energy Directive in which the 28 member states have agreed to a target of 20% of energy from renewables by 2020. In 2011 this was 10%, of which 4.8% was from the use of wood and wood-waste material [24]. It is projected that more than 10% of final energy consumption will be derived from biomass by 2020 [25] with forest biomass likely to be a significant component [26].

There are an estimated 2.5Mt of collectable biomass in South Africa, and significant areas of South Africa (predominantly located within a 200km coastal buffer) are furthermore ideally suited to forestry [27]. Environmental conditions enable trees to reach maturity after ca. 15 yrs, whereas in Europe and North America trees need more than 50 yrs [28]. In South Africa, thinnings and plantation waste can be utilised as early as four years after planting, in contrast to much longer periods in the northern hemisphere (+10 yrs) [28]. SSA has the potential to substantially contribute to the supply of bioenergy [29], and there is a considerable surplus of biomass production compared to demand in the developing world [30].

With the pellet bioenergy market going from strength to strength in the US and Europe, some might assume that the US and European model could be directly transferred to South Africa. With ample affordable labour [27] and a productive timber sector, South Africa is potentially an ideal location for a pellet bioenergy industry. However, to date, only four pellet plants have been established in South Africa, all of which closed within six years of being commissioned (**Table 1**). Obviously unexpected events took place which the industry had neither anticipated nor prepared for.

Table 1. Details of the four former pellet plants in South Africa. Direct job creation - onsite jobs created. Indirect job creation - jobs created in the delivery of raw material to the plant and pellets to the harbour

A complex set of interacting factors, which occur at different scales, potentially affects the resilience of woody-biomass operations. The forest industry consists of a variety of interrelated and interconnected sectors within their respective supply chains and variations in one part of the supply chain generally propagate into other areas (e.g. the downturn of the housing market results in a reduced demand for timber, which in turn results in decreased availability of wood chips, and thus a reduced availability of raw material for bioenergy [31]). Other factors which make bioenergy complex include: optimal timber growing areas being spread over large areas which are challenging to access due to unreliable infrastructure (i.e. plantation companies usually only maintain access roads during harvesting); the need to optimize fluctuating transportation costs as the raw material is bulky with relatively low density; and the need to obtain and store raw material with a low moisture content in order to reduce costs associated with drying the material ready for processing [32]. These characteristics are known to contribute to the high cost and complexity of forest biomass logistics [33]. These dynamics interlink with the ecological systems generating the biomass, forming a complex social-ecological system (SES).

Social-ecological systems refer to social systems in which some of the interdependent relationships between humans are mediated through interactions with ecological units [34].

They are complex and adaptive [34], often functioning as a nested hierarchical structure, with processes occurring within different sub-systems at different rates and scales [35, 36]. For example, within the woody-biomass SES interactions can occur at a local 'plantation' level, at a landscape level (geographical area which features favourable conditions for the growing of timber), and at a national / international level (area where pellets are sold, and groups have interest in policies associated with forestry practices).

Concerns around the environmental impacts of biomass harvesting have led to the development of sustainability criteria, indicators and certification as a way of monitoring the sector [37, 38, 39, 40, 41]. Although generally considered useful when applied to bioenergy production [38, 41, 42] and forest management [43], limitations associated with the use of criteria, indicators and certification have also been acknowledged [41] (**refer to Supplement 2 in supplementary material**). Alternative approaches for assessing the sustainability of the woody-biomass pellet sector are needed, and furthermore, such approaches must take into consideration the complex SESs which comprise and surround the woody-biomass industry. To date no investigation has taken place into the contributing factors undermining the resilience of the four failed South African pellets plants. This paper documents a first attempt at developing this understanding using a SESs theory approach. The paper also identifies the key risks to the establishment of a resilient woody-biomass sector in South Africa, and provides mitigation measures to reduce these risks.

2. METHODOLOGY

The wood pellet industry in South Africa is clearly a complex SES which would benefit from formal description and analysis of interdependencies. For this purpose we selected a relatively simple framework (hereafter referred to as the ‘original’ framework) that separates the SES into the following four entities: (a) the resource; (b) the resource users; (c) public infrastructure and

(d) public infrastructure providers, and considers two types of disturbance, external and internal [34]. The value of this approach is that it provides an unambiguous mechanism for disaggregating the entities of a SES and facilitates the systematic identification of the relationships between them. This approach has been further developed and applied in a number of settings [44, 45, 46], including a case study which identified and evaluated potential resilient estuary-based enterprises to encourage economic empowerment in South Africa [47]. Based on the published literature, and technical documents and understanding relating to the four pellet plants, the SES was described and represented **(Figure 2)**. In doing so it was recognised that conceptualising the SES would require representation as a set of interlinked SESs operating at different spatial scales; one at the localised scale of the pellet production and the other at the broader scale of the regional energy supply SES.

As a starting point for the development of the risk assessment, all four of the former pellet plant managers were asked in a telephonic interview (August 2014) to explain the challenges experienced which contributed to the failure of the plant. This was done to obtain a broad view of possible risk areas. Following this, sustainability indicators and related criteria used in the bioenergy sector were reviewed, along with supply chain optimisation strategies. The latter was undertaken as these are likely to act as drivers for the industry and thus have the potential to contribute to risks in the bioenergy sector.

A methodology to assess the risks associated with Natural Resource-based Enterprises (NRBEs) which caters for the developing world social-ecological and economic conditions has been developed and applied elsewhere [47] and was tested further in this study. Based on this approach, and in conjunction with the interlinked SESs shown in **Figure 2**, a comprehensive set of open-ended questions relating to the elements and interlinkages was compiled. These questions were then addressed to all four of the former pellet plant managers, during a subsequent series of telephonic interviews (September 2014). These interviews, along with understanding derived from a literature review on potential benefits of and constraints to the woody-biomass sector, were used to populate the risk assessment. The risk assessment is intended to display the variety of risks which have the potential to arise with each interaction between the different elements shown in **Figure 2** (e.g. between infrastructure and raw material suppliers) and which are described in **Table 2**. This includes 14 interactions within the pellet production SES and 8 interactions within the energy supply SES. For each of these interactions, the risk assessment listed a series of questions relating to potential risks and suggests possible mitigation measures. Different levels and types of risks (e.g. short-term, level 1 – machine failure, long-term, level 2 – supply of raw material and seasonal demand for product) are differentiated [31], and were used in this assessment. The approach focused on level 2 long-term uncertainties; however some general short-term level 1 risks were also included as many individual (or combination of) short-term level 1 risks could be more detrimental to a pellet plant compared to a single long-term level 2 risk. Once completed, the initial risk assessment was sent to the four former plant managers for review, with responses recorded via several open-ended questions (see Section 3.3). The initial versions of the woody-biomass risk assessment and SES framework were then amended with feedback from the former plant operators (**Table 3**). The SES in **Figure 2**, and the associated risk assessment (**refer to Supplement 3 in the supplementary material**) therefore represent the result of an iterative process.

Figure 2. The South African woody-biomass social-ecological system framework. * Physical - transformation and communication infrastructure; governmental – legal and regulatory infrastructure; social – knowledge and skills infrastructure. ** Production process – input of raw material, pre-treatment and pelletising, delivery of product (output). Refer to Table 2 for definitions of the different interlinkages

Table 2. Defining elements of the South African woody-biomass social-ecological system framework

Table 3. Extensions to the Anderies et al. (2004) social-ecological system conceptual framework

3. RESULTS

This section firstly presents and explains the different aspects of the woody-biomass conceptual framework. This is followed by a summary of the main challenges experienced by the former pellet plant managers which contributed to the failure of the plant. This section concludes with analysis of the review of the risk assessment by the former pellet plant managers.

3.1 A woody-biomass SES framework

Figure 2 shows a global SES comprising two interlinked SESs: i) pellet production SES – the SES from where the raw material is collected, pellets are produced within and a portion of the pellets are used; and ii) energy supply SES – the SES where the pellets are used, but the material to produce them is not sourced from this SES. Although both SESs are part of one large global SES, the two are separated as there are several factors which are only applicable to either the pellet production or energy supply SES. The arrows within and between the different elements of the framework indicate the interlinkages and interdependences within the respective SESs, and are described in **Table 2**.

In the pellet production SES, which functions at a local scale, 'competing resource users and actors' emphasises that competition for raw material is a key factor which affects the functioning of the plant. The framework also highlights that the actual 'raw material', the 'physical', 'governmental' and 'social' infrastructures and those responsible for supplying these 'infrastructures' (referred to as 'infrastructure providers') are the other key elements which affect the plant. The actual plant is included within the 'infrastructure' component, and this is accentuated by the inclusion of 'internal business dynamics'. The 'product' is located within the pellet production SES as it is produced within that SES. There may also be demand for the product within the local SES from 'raw material suppliers' (e.g. sawmills needing heat to dry timber), 'competing resource users and actors' (e.g. poultry farms who use sawdust for bedding but also require energy for heating) and 'infrastructure providers' (government who is responsible for providing and maintaining roads, and also need power for government services, such as hospitals).The framework represents the pellet production process through displaying 'raw material' as an 'input', 'infrastructure' as the manufacturing process which involves 'physical infrastructure' (e.g. the plant), 'social infrastructure' (e.g. skills, technology and knowledge) and 'governmental infrastructure' (e.g. laws and policies governing operations and demand for product). The 'output' of the production process is the pellets which is the 'product'.

In the energy supply SES, 'product users and actors' indicates that this group can have demand for pellets, but also have access and a desire to use other energy resources. 'Energy resources' highlight that competition (e.g. from other pellet producers) or availability of other energy resources (e.g. coal, wind) could impact on the demand for the product. 'Infrastructure' draws attention to the fact that the following can impact on the demand for the 'product': i) 'physical infrastructure' which refers to the accessibility of the 'product'; ii) 'social infrastructure' which refers to the knowledge of the availability and application of pellets; and iii) 'governmental infrastructure' which refers to legislation and policy which supports or discourages the use of pellets. Also indicated are the 'infrastructure providers' which highlights the need to consider those responsible for provision of the 'infrastructure'. The framework also encourages the consideration of the preparedness for 'external biophysical forces' and 'external social, economic and technological forces' in both SESs.

3.2 Key factors underpinning the failure of the pellet plants

Contamination and European technology not appropriate for South African conditions

Initially all four plants were designed and established based on European technology and standards. The raw material for Plant B was collected from several different sawmills, unlike in Europe where pellet plants obtain sawdust from adjacent sawmilling operations. The raw material in Europe is managed in such a way that it does not come into contact with the ground, thus expensive technology is not required for screening the raw material. Plant A representative confirmed that harvesting practices, sawmill management and housekeeping were extremely poor in South Africa, thus contamination from soil (silica), rocks and non-organic waste (e.g. plastic and metal) was significantly higher compared to European and US counterparts. High silica content not only comes from poor harvesting practices; timber grown in South Africa is also naturally higher in silica compared to timber grown in Europe or the US, due to soil type. This contamination not only affected pellet quality, but increased the threat of explosions during the drying and milling processes. Once operational, it soon became apparent to Plant A that the decontamination and preparation of particle size prior to drying was paramount. It took ca. $3 million to hone the skill and develop technology to decontaminate and prepare raw material prior to pelleting at this plant. This new technology included the development of a pelleting die ideal for use with contaminated raw material, and which could be refurbished up to four times, compared to twice (the industry norm). As well as the die being suitable for South African conditions, this advancement also made the die 50% more cost effective and thus reduced maintenance costs.

The Plant D representative indicated that a significant contributor to contamination was when general workers operating the sawmill confused raw material containers with waste receptacles. This confusion was as a consequence of the high turnover of unskilled workers and a lack of training. This confusion increased contamination which on one occasion resulted in an explosion within the hammer mill when a small piece of metal was struck by a blade. This first explosion caused a second explosion in the holding hopper beneath the hammer mill, so powerful it moved a concreted I-beam 0.3m. At another plant, a dust explosion during the pellet production process fatally injured an operator. This explosion was the result of contaminated raw material, although the exact type of contaminate which caused the explosion is still unknown.

The Plant A representative suggested that due to the ever-growing shortage of global raw material, the experience acquired in South Africa to manufacture Grade A pellets from contaminated material may become all-important to this industry in the future. The Plant D representative stressed that conditions in South Africa are completely different to that of Europe and the US.

Costly Logistics

All four plants identified that logistics was a fundamental risk to the industry, especially as all products were exported. Only Plant A was considered well-positioned in terms of distance to raw material and port. The other plants had an average round trip of 500km for raw material (for Plant A it was 80km). All representatives identified that the running costs (km^{-1}) were very high and inefficient. Although transportation costs were considered during the feasibility phase, it emerged that transportation providers escalated costs as demand increased due to a lack of competition. Plant A addressed this issue with running return loads (delivering product and returning with raw material). The Plant B representative indicated that it was 30% cheaper to deliver pellets to the UK, compared to delivering the same amount to Cape Town, Western Cape, from northern Zululand (3 000km return trip). Plant A saved 30% on logistic costs by owning and operating its own trucks in year three. The Plant C representative saw logistics in South Africa as being dominated by road transportation, as the rail system is poorly maintained and unreliable and sea freight is too expense over short distances (<1 500km). The Plant D representative told of truck turnaround times being frequently doubled due to congestion on the roads and at the harbour.

Unreliable supply of raw material

The establishment of Plant C was based on obtaining raw material from a major timber supplier that withdrew its commitment after being offered a more lucrative arrangement from a non-bioenergy enterprise. This played a key role in the collapse of this plant.

At Plant D the majority of timber producers in the local area choose to continue to send their raw material overseas instead of supporting the local pellet industry. The representative attributed this reluctance to ignorance, poor management and an outdated mindset, and was of the opinion that greater returns for the raw material suppliers can be achieved if the raw material is converted into pellets.

Lack of ancillary services and technical knowledge

The Plant C representative raised the issue of a lack of ancillary services (e.g. welders, boiler makers, fitters and turners, electricians and millwrights) as being a key cause of plant failure, and attributed it to the abandonment of technical training colleges and apprentices by the government post-1994. He added that although these technical colleges had recently reopened, the level of skills required to maintain pellet plants was seriously lacking, and this was further compounded by a lack of technical skills in associated support companies (e.g. IT) which were needed to build and service the plants.

Plant A was supplied capital equipment that did not achieve the stated production rate, and when taken to task the suppliers refused to replace the under-performing equipment. This resulted in the plant performing 15 Mg yr^{-1} under capacity. This occurred due to a lack of skills and knowledge of South African conditions.

3.3 Review of the risk assessment by representatives from the four former pellet plants

The representatives were asked three open-ended questions in review of the initial risk assessment:

1. *Have any risks been omitted or not adequately addressed in the risk assessment?*

Investor exploitation and a lack of support from government and banking institutions

Although investor confidence featured in the risk assessment, three plants considered it required much more emphasis. The consensus was that there was no support from government, venture capitalists or the banking sector to fund pellet plants in South Africa. Plant C representative referred to the large bank investments associated with fossil fuels and their aversion to supporting the renewable fuel industry. Plant B indicated that overseas investors view South Africa as a poor investment option and those which do venture into the country frequently exploit projects with high interest rates and unfair contractual conditions. Plant A representative gave the example of receiving R85 million from a UK investor, and then undergoing an 18 month environmental authorisation process. Of the R85 million received, the plant was forced to repay the investor R33 million in interest during the first year, before construction had even started.

Plant A obtained investment indirectly from the South African arms trade offset deal, which the implementers were unaware of at the conception of the project, as these funds were channelled through a major UK based bank. Once an investigation was launched into corruption associated with the arms deal, the investor and bank called in the loan, which resulted in the collapse of the plant.

Mismanagement and a lack of technical skills

All plant representatives suggested more focus on management issues and a lack of skills. At all plants, except A, administrative mismanagement and an absence of technical skills at an operational level significantly contributed to plant failure. Conflicting agendas between management and investors was also a key cause of failure at all plants. It was Plant A's intention to grow the pellet industry in South Africa and it regularly offered technical advice to the other three plants. However, personal agendas prevented these plants from accepting advice. Plant B experienced an investor interfering technically from an uninformed perspective. This interference created ill feeling between the investor and operations management.

2. Are the mitigation measures adequate, realistic and manageable?

Securing raw material supplies

Although all representatives agreed with securing long-term contracts with raw material suppliers, in reality all claimed that this was not possible. The consensus was that raw material suppliers are becoming increasingly aware that waste material is gaining value, and do not want to be locked into long-term contracts as they wish to keep their options open. This opinion is valid, given that in Europe in 2005 the cost of raw material was 5 $ t^{-1}, and by 2010 it had increased to 50 $ t^{-1} [27]. Although the woody-biomass sector is still in its infancy, the competition for raw material has already become a serious challenge in German and several other European countries [52]. All representatives thought owning plantations was a potential solution, however they had reservations about long-term land tenure due to political conflict in South Africa.

Forest productivity, including site conditions, soil characteristics, harvesting methods, vegetative cover, and management history should be considered when securing supply [53, 54]. However Plant A, B and D representatives stressed that it was impossible to become involved in this part of the process, because in this industry “beggars can't be choosers” and “you must take what you can get”. Generally the raw material received was waste, thus “it is impossible to be picky about the source of the material”.

Legislation, guidelines and standards must be specific to South African conditions

The three plant representatives were adamant that the development of legislation and guidelines must not be based on developed world experience, as the South Africa situation is entirely different. A key difference is that the specification standards are based on EU and US wood types and conditions. Thus in South Africa the quick growing trees (15 yrs compared to 55 yrs in the EU and US) vary in material quality and therefore the EU specifications are unlikely ever to be achieved, without great expenditure on technological advancement.

Irrigation has been proposed as a means of promoting growth during drought [52]. The Plant B representative raised the concern that South Africa was a water sparse country and that afforestation was already seen as a stream-flow reduction activity. Thus to encourage additional irrigation was unlikely to be favourably received by government or the private sector. The Plant C representative also had concerns about this suggestion, as irrigated water in South Africa could have contaminants which would affect the emission specifications of the pellets (e.g. high chlorine levels).

3. *Are there any mitigation measures missing from the risk assessment?*

The Plant D representative recommended that to reduce the potential for contamination, pellet plant management must be involved with raw material management before it is harvested, and that they must consider investing in demarcated hubs at each sawmill. The Plant C representative recommended that investors must have adequate funding for unforeseen events, due to the unpredictability and complex components of the South African pellet industry. The Plant B representative recommended that the anticipated cost of building a plant must be doubled due to the lack of logistics in South Africa, and also recommended that a South African biomass association be formed which offers skills, support and technical human resources to help establish, operate and maintain the pellet plants.

4. DISCUSSION

It has already been recognised that the key risks to a sustainable South African pellet industry are a mix of social, ecological and economic constraints, which need to be overcome before Africa is prepared for the woody-biomass industry [29]. From a social perspective, the risk assessment identified that training (from basic housekeeping to advanced technical knowledge), skills, education and awareness of the benefits associated with the industry were lacking. From an ecological perspective, contamination caused by a high silica content of wood waste (both naturally occurring and through poor harvesting practices) and the spatial location of plantations and sawmills, increased the cost of pellet production. From an economic perspective, the cost of logistics, investor exploitation, turbulent interest rates and fixed costs were fundamental to the resilience of a pellet plant. This research illustrates that the SES surrounding the pellet industry is highly complex, with many interconnecting relationships.

External review of the risk assessment highlighted that the plants had adaptive capacity (and thus increased resilience) in some aspects. For example, Plant A chose to purchase its own trucks, use return loads to counter increased transportation costs, and develop technology to cope with the unique South African conditions. However in relation to other aspects, such as corrupt investors, adaption to cope with this risk was not possible.

The initial risk assessment included the majority of the key risks which affected the resilience of the four former plants. However the initial draft failed to include: i) Investor funding exploitation and a lack of support from government and banking institutions; ii) internal mismanagement; iii) sufficient funding to address unpredictability associated with construction and initial operation; and iv) legislation, guidelines and standards needing to be specific to South African conditions. Two aspects which were identified, but required more emphasis, were contamination management and a lack of technical skills. All these risks relate to financial or technical internal business operations, or are linked to conditions in South Africa where woody-biomass is a new industry and where support for the industry is low, and corruption is high. As the risk assessment was predominantly based on literature from the developed world, failure to identify investor corruption is not unexpected, as this risk is more commonly associated with business in developing countries. This is demonstrated by South Africa being ranked 72nd out of 177 countries in 2013 for perceived corruption, obtaining a score of only 42 out of 100 (where 0 means that a country is perceived as being highly corrupt, and 100 means it is considered 'clean') [55].

The NRBE framework [34] was used elsewhere [56] where it was found that the risks not identified through application of the framework were predominantly economic, and were related to the internal business dynamics of an enterprise; and those that were identified were all linked to social aspects within a SES. This was not considered entirely unexpected as the SES conceptual framework [34] is not directly concerned with economic impacts, but focuses on social and social-ecological interactions at a landscape level [57]. For this reason, the woody-biomass SES framework was amended to reflect these omissions (see **Figure 2, Tables 2 and 3**).

The use of SES theory for this application has highlighted that there can be resilient and non-resilient activities occurring within the pellet production SES simultaneously, and at different scales. For example, the collection and processing of sawdust prevents illegal dumping. This practice reduces potential for groundwater contamination and increases the resilience of the surrounding ecological environment. However, at the same time, the long-term effects of woody-biomass removal from plantations may negatively impact on soil productivity if not managed correctly. This practice could be amplified in South Africa, in comparison to Europe and other temperate regions, as the warmer climate increases rotation cycles, and thus more frequent removal and soil disturbance is experienced over time.

Ecological risks were identified in the risk assessment (e.g. possible reduction in soil fertility from the removal of plantation waste, reduced water availability in catchments due to timber plantations using more water than natural vegetation, loss of biodiversity from converting natural areas to plantation as demand increased). However, as previous SES frameworks are based on social and social-ecological interactions, and not ecological interactions, there is concern that not all risks associated with ecological components and interactions are adequately addressed when applying earlier SES theory to NRBEs. Although the original framework [34] did include external biophysical factors on the 'resource' and 'infrastructure' (arrow 7), they did not consider biophysical interactions as a consequence of 'resource users' actions. The woody-biomass SES framework now includes multi-tiered ecological variables (which show that there are many different ecological variables), and arrows which interlink these variables (arrow 14) (**Figure 2, Tables 2 and 3**). **Table 3** provides expanded explanations for the amendments made to the original framework [34]. As the authors consider the SES conceptual framework to be applicable to other NRBEs which feature a production process, **Table 3** has not been made woody-biomass specific. To realise the many benefits associated with a sustainable and resilient South Africa woody-biomass industry, strategies to achieve this are provided in **Table 4**.

Table 4. Strategies towards the establishment of a resilient pellet industry in South Africa

4.1 Limitations and further work

This paper documents the first attempt at developing a practical tool which has the potential to increase the resilience of a woody-biomass industry in South Africa. Although basing the risk assessment on SES theory increases the level of confidence in the results obtained from implementation, far more work is required before a robust risk assessment is available. In its current form, it can be used at a broad level to highlight key aspects which must be considered as part of a feasibility assessment for a new plant. However, social, ecological and financial data relevant to the pellet industry in South Africa is deficient, thus the accuracy of the information to populate it may be poor, which could result in incorrect conclusions. Even with this limitation, the risk assessment provides a good starting point for the development of a robust and practical tool. This tool, when complete, could also be transferable to the agricultural residue biomass sector with some amendments, even though limited work has been undertaken on agricultural residue in comparison to woody-biomass. The SES conceptual framework presented in this paper could also be applied to other NRBEs which are based on a production process.

Although the risk assessment has been amended to incorporate all risks identified by the former plant representatives, as the plants were not operational for a long period, there is a danger that some fundamental issues about the overall system, and particularly ecological components, have not been identified. The short-term operation of the plants could also result in the SES framework not being considered to have been fully applied to this application, as the effects of the use of the resource on the ecosystem supplying the resource could not be assessed over a prolonged period. With the dearth of ecological data available for South African conditions, the accuracy of results obtained from any attempts at predictive ecological modelling might be questioned.

The representativeness and reliability of the results when implementing the risk assessment, or final tool, will be strongly dependent on the level of stakeholder engagement. A limitation of this paper is that it only involved representatives from the four failed pellet plants. Engagement with other stakeholders (e.g. competing resource users and actors) may have yielded additional results. Industries which are not linked to the pellet production SES (e.g. swine, dairy and meat processing industries) should be consulted, as this might lead to these industries meeting their sustainability goals (which might increase their resilience), and to amendments or additions to the risk assessment and accompanying SES framework. Thus further work in both of these areas is suggested.

A potential starting point to address these limitations is to examine the risks in more detail across multiple scales. For example, at a pellet plant level, further investigation into the internal operational dynamics should be undertaken (e.g. trade union strikes, stealing of product). Although these dynamics may not be biomass-sector specific, they still need to be incorporated into a comprehensive risk assessment. At a landscape level, further investigation into the needs of competing resource users and actors, and the possibility of cross-sector management to help mitigate against these risks, is also suggested. This could include combining logistics (e.g. the timber industry could 'load-share' with the woody-biomass industry: trucks could be used to transport logs and biomass material at the same time) and adopting trade-off strategies with competing resource users (e.g. subsidised pellets could be sold to the poultry industry as an alternative to woodchips for bedding is used). At a national level, further investigation into the social, economic and ecological implications of an emerging woody-biomass industry, which could include the ability of the country's judicial system to control the establishment of illegal plantations, and the possibility of government transferring interest from fossil fuels to biomass, is recommended.

One aspect not specifically addressed in the original framework [34], and which is highlighted by others [56], is that of monitoring, which is particularly pertinent to ecological risks and impacts. Although the original framework [34] included rules and regulations (under 'infrastructure') and those that police these (under 'infrastructure providers'), there is no prompt for ongoing assessment and monitoring. However, we recommend that the risk assessment, or final tool, be implemented prior to an enterprise being established, as this will hopefully give the enterprise a better chance of being resilient. Furthermore, in order to enhance the operational resilience of the enterprise, the assessment should be repeated periodically as it is anticipated that further risks (and associated mitigation measures) will emerge during the lifetime of the enterprise. Prior to the assessment being repeated, the SES conceptual framework should be referred to, in conjunction with the previous results, and the assessment, or tool, should be updated, as it is likely that the interlinkages and interdependence within the SES will change as the enterprise expands and evolves. This progressive application links well with strategic adaptive management, as the first assessment of the SES feeds into initial management vision and objective setting, and the second (and further assessments, as required) are linked with review and learning.

5. CONCLUSION

The SES analytical framework provided a useful construct in which to analyse the dynamics of the fledgling woody pellet industry. This approach revealed useful lessons relating to a broad spectrum of risks potentially facing a woody biomass enterprise, from which the wider industry can learn. These include risks relating to: (a) appropriateness of the technology for local conditions, including contamination; (b) logistics and transport; (c) reliability and long term sustainability of the raw material supply; and (d) ancillary services and technical skills and knowledge. It is recommended that the SES analytical framework, and specifically the risk assessment component, be used to evaluate key potential risks that must be considered as part of a feasibility assessment for any new pellet plant. It is suggested that this will provide a good foundation for the development of a robust and practical woody-biomass planning tool, which, together with stakeholder input including both competitors for the raw materials and potential users of the biomass product, will hopefully support the establishment of a resilient biomass industry.

The risk assessment could also be useful to inform the overall question of the viability of the pellet plant industry in South Africa, or at any other location. However, further investigation into the long-term ecological risks associated with a woody-biomass industry under South African conditions is required. Future work is also proposed to focus on analysing risks in greater detail at multiple scales, including the local plant-level scale, landscape scale and national/international scale.

There are many benefits associated with a South African woody-biomass industry, however many social and economic risks exist (e.g. lack of skills, knowledge and education), which are typically associated with the developing world, and require considerable attention in order for the many benefits associated with this emerging industry to be realised in this country. An important element which future woody-biomass enterprises must address as a priority is the need to develop a local market for the pellets. Having a local market addresses many of economic risks associated with establishing the industry in South Africa. Publication of this work may encourage decision-makers to revisit the use of woody-biomass for power provision on a national scale, and those in positions of authority to take action to improve the chances of a resilient wood-pellet industry in South Africa.

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Supplementary Material

Supplement 1. Potential ecological, social and economic benefits attributed to the use of woody-biomass

Supplement 2. Limitations associated with the use of criteria, indicators and certification use to monitor biomass harvesting, bioenergy production and forest management

Supplement 3. Woody-biomass risk assessment showing potential risks and associated mitigation measures

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Table 1. Details of the four former pellet plants in South Africa. Direct job creation - onsite jobs created. Indirect job creation - jobs created in the delivery of raw material to the plant and pellets to the harbour

Plant	Details	Plant	Details
Plant A	Located within KwaZulu-Natal Midlands	Plant C	Located within Mpumalanga
	Built to produce 65 000 t yr^{-1}		Built to produce 75 000 t yr^{-1}
	Operated at 98% capacity		Operated at 5% capacity
	325 000 t sold to Europe		1000 t sold to Europe
	Date commissioned: 2008		Date commissioned: 2010
	Date closed: 2013		Date closed: 2012
	Operated for five years five months		Operated for one year five months
	Direct job creation: 52		Direct job creation: 51
	Indirect job creation (est.): 25		Indirect job creation (est.): 22
Plant B	Located within northern KwaZulu-Natal	Plant D	Located within the Eastern Cape
	Built to produce 75 000 t yr^{-1}		Built to produce 80 000 t yr^{-1}
	Operated at 10% capacity		Operated at 20% capacity
	800 t sold to Europe		10 000 t sold to Europe
	Date commissioned: 2008		Date commissioned: 2009
	Date closed: 2010		Date closed: 2012
	Operated for two years one month		Operated for three years
	Direct job creation: 60		Direct job creation: 55
	Indirect job creation (est.): 25		Indirect job creation (est.): 25

Table 2. Defining elements of the South African woody-biomass social-ecological system framework

Pellet production SES	Definition / link	Examples
Raw material	Material to power the pellet plant and to produce the product (input for the production process)	1. Sawmill waste[48] 2. Short-rotation purpose-grown timber [17] 3. Low quality wood from small trees, branches and other slash [49, 50] 4. Alien vegetation infestations (rural) 5. Urban and rural municipal and domestic garden waste 6. Plantation thinnings and harvest waste [48, 51]
Competing resource users and actors	Those who utilise the same raw material required for pellet manufacture	1. Sawmillers – material burnt to generate heat / substitute for wood drying 2. Paper, pulp and particle board manufacturers 3. Rural poor – plantation waste and alien vegetation collected for heating and cooking 4. Plantation companies – thinnings sold to fencing and pallet manufacturers or burnt to increase soil fertility 5. Municipalities – alien vegetation used as a 'balancer' to reduce contaminants from other landfill or sold for a purpose (e.g. composting) 6. Poultry producers – material for bedding 7. Plastic and cement manufacturers [21]
Infrastructure	**Physical**	
	Transformation and communication infrastructure	All manmade alterations to a landscape, transportation and telephonic / digital communication • Transfer of raw material to pellet plant, and distribution of product to users [20] • Plant which produces the product • Stoves, burners and furnaces which burn pellets • Services required to produce and transport product (electricity, roads, harbours, water, waste disposal, communication networks)
	Governmental	
	Legal and regulatory infrastructure	Laws in the form of acts, regulations, policy documents and customary regulations, and government / political structures (e.g. structures to define powers and responsibilities) • Local, national and international legislation and policies which i) promote and support the use of pellets; ii) discourage the use of competing raw material users; iii) provide the associated services / infrastructure required to support product production; and iv) control the different aspects of the production process (e.g. labour law and air emission controls)
	Social	
	Knowledge and skills infrastructure	Scientific / technical knowledge • The level of technical knowledge available for the construction, operation and maintenance of the i) pellet plant; and ii) equipment which uses pellets • Ability of educators and media to inform the public on the use of pellets

Infrastructure providers	Those responsible for the provision of required infrastructure	1. Governmental departments responsible for: • Implementing the governmental infrastructure (see above) • Supporting economic development 2. Private sector responsible for: • Providing the required transportation, communication etc. (e.g. privately owned trucks, telecommunications networks) • Middle-men who sell stoves, burners and furnaces
Product	Pellets as the output of the production process	Woody-biomass pellets which are utilised by those within the production process SES, and those located within energy supply SESs
Interactions within pellet production SES		
1	Between raw material and competing resource users/actors	Competition between the pellet producers who need biomass for the manufacturing process (e.g. sawdust to fuel the kiln which creates heat to make the pellets) and to make the product, and other industries which utilise biomass (e.g. composting, animal bedding enterprises)
2	Between competing resource users/actors and infrastructure providers	The promulgation and enforcement of legislation and policies which favour one resource use over another (e.g. laws which specify that a portion of plantation waste must go to renewable energy)
3	Between infrastructure providers and infrastructure	The provision, monitoring and maintenance of infrastructure by those responsible for providing infrastructure (e.g. the continual up-dating of laws and regulations to be in line with best practice, such as air emission standards)
4	Between infrastructure and raw material	Infrastructure or lack of infrastructure which enables raw material to be utilised (e.g. roads which permit biomass to be accessed in remote areas, laws which control the combustion of biomass)
5	Between infrastructure and raw material dynamics	Legislation, physical infrastructure and technical knowledge which impacts on the availability and / or nature of the raw material (e.g. scientific knowledge can help towards optimising timber yield)
6	Between competing resource users/actors and infrastructure	The impact of actions of the pellet producers and other resource users/actors on the availability or nature of infrastructure (e.g. not respecting the weight limit on plantation access roads could lead to the roads becoming impassable)
7	External biophysical forces on raw material, infrastructure and infrastructure providers	Severe weather and natural disasters (e.g. excessive rainfall) could: i) hinder harvesting, and thus reduce the availability of timber for the sawmills, which in turn will reduce the availability of sawdust and off-cuts for bioenergy; and ii) increase the moisture content of raw material which will increase production costs)
8	External social, economic and technological forces on infrastructure providers, infrastructure and raw material	External forces could include, changes in political system (e.g. war, conflict or change of government may cause a loss in investment), advancements in technology (e.g. advancements which make other renewable energies more or less desirable compared to woody-biomass)
9	Demand for product by competing resource users/actors	Those located within the pellet production SES and who have demand for the pellets (e.g. a poultry farmer who uses pellets to heat poultry houses, but also uses sawdust as bedding)
10	Demand for product by raw material suppliers	Raw material suppliers may have demand for the product (e.g. a fencing and pallet manufacturer who provides the plant with sawdust, may use wood pellets to dry their timber prior to manufacture)
11	Demand for product from infrastructure providers	Those responsible for providing the infrastructure who have demand for the product (e.g. electricity providers may use pellets to produce power)
12	Demand for product by	Those who use the same infrastructure as the woody-biomass plant (e.g. use the same roads or are governed by the

	infrastructure users	same municipal by-laws) but are not infrastructure providers, raw material suppliers or competing resource users/actors (e.g. a nearby abattoir which burns wood pellets to heat water)
13	External demand for the product	Those who have demand for the product and who are not located within the same SES as pellet producers. They do not depend on the same infrastructure or compete with the same resource users/actors as the pellet plant (e.g. when the pellets are shipped overseas)
14	Ecological interactions	The interactions between ecological variables as a consequence of the enterprise (e.g. soil nutrient decline as a result of long term harvesting of biomass from a forest plantation).
Energy supply SES		
Product users/actors	Those who have demand for the product but do not rely on the same raw material for another purpose	1. National enterprises • Companies located within the same country, but which do not compete for the same raw material. These product users/actors may be governed by the same overarching legislations (e.g. a country's constitution) however there may be different local by-laws, regulations etc. These product users/actors are likely to be a significant distance from the plant 2. International enterprises • Companies located outside of the country of pellet production. These countries are governed by different legislation and controls, and may have access to different technologies due to scientific knowledge or environmental situation
Energy resources	Alternative energy sources	Changes in policy, legislation, profitability and / or evolving scientific knowledge could result in the preference of one energy source over another by a country or enterprise (nationally or internationally). Alternatives include: biofuel, solar, wind, hydro, thermal, traditional fossil fuels, and the supply of pellets from a different SES.
Infrastructure required to enable the delivery and use of the product	Physical Transformation and communication infrastructure	All manmade alterations to a landscape, transportation and telephonic / digital communication • Distribution of product to users (e.g. trucks, roads) • Services required for the product to be used (e.g. burners which are suitable for pellets, electricity infrastructure to carry power to users)
	Governmental Legal and regulatory infrastructure	Laws in the form of acts, regulations, policy documents and customary regulations, and government / political structures (e.g. structures to define powers and responsibilities) • Legislation, policies etc. which support: i) the use of pellets; and ii) services / infrastructure required to utilise the product
	Social Knowledge and skills infrastructure	Scientific / technical knowledge • literacy level which enables users to understand the benefits and constraints of using, and the knowledge required to efficiently utilise the pellets
Infrastructure providers	Those responsible for the provision of required infrastructure	1. Governmental departments responsible for: • implementing the governmental infrastructure (see above) • supporting economic development 2. Private sector responsible for: • Providing the required transportation, communication etc. (e.g. privately owned trucks, telecommunications

		networks) • Middle-men who sell stoves, burners and furnaces
Interactions within energy supply SES		
1	Between alternative energy resources and product users/actors	The demand for pellets may increase or decrease as a result of the availability or preference to an alternative energy resource (e.g. pellet production may become established in a country where it was not previously available.)
2	Between product users/actors and infrastructure providers	Legislation, policies, agreements and regulations which support or do not support the use of pellets (e.g. the introduction of carbon tax will encourage the use of renewables)
3	Between infrastructure providers and infrastructure	The provision, monitoring and maintenance of infrastructure by those responsible for providing infrastructure (e.g. the maintenance of pellet burners at a facility, or ships and harbours used to transport pellets)
4	Between infrastructure and alternative energy resources	Infrastructure or lack of infrastructure which may led to the favouring of one energy resource to another (e.g. the absence of a harbour, or a harbour which is unable to receive pelletised product)
5	Between infrastructure and alternative energy resources dynamics	Legalisation, physical infrastructure and technical knowledge which impacts on the utilisation of different energy resources (e.g. a lack of scientific knowledge may result in some governments favouring fossil fuels as they are wary of change)
6	Between product users/actors and infrastructure	The impact of actions of the product users/actors on the availability or nature of infrastructure (e.g. the demand for pellets may result in improved transportation networks, or the installation of modern, clear and efficient kilns)
7	External biophysical forces on alternative energy resources and infrastructure	Severe or changes in weather may result in an increased or reduced demand for alternative energy sources (e.g. the demand for pellets produced from outside the pellet production SES may increase if local pellet supplies have been affected by flooding)
8	External social, economic and technological forces on infrastructure providers, infrastructure and energy resources	External forces could include changes in political system, advancements in technology (e.g. advancements which make other renewable energies more or less desirable compared to woody-biomass)

Table 3. Extensions to the Anderies et al. (2004) social-ecological system conceptual framework

Amendment	Explanation
Raw material replaces 'resource'	This substitution highlights that the enterprise is based on an ecological good which is unprocessed. The multi-tiers behind this component indicate the different ecological components with which the raw material interacts.
'Competing' and 'actors' added to 'resource users'	'Competing resource users and actors' emphasises that competition for raw material is a key factor which affects NRBE. 'Actors' has been introduced as it is important to consider the behaviour of third parties who are not direct users or consumers of the raw material in question.
Multiple SESs	Three nested SESs are indicated: the global SES comprising two interlinking SESs. 1) Pellet production SES (local SES) – where the raw material is collected from, and a portion is used by those who are governed by the same rules and / or use the same infrastructure as the NRBE; and 2) Energy supply SES – where the product is used, but the material to make the product is not sourced from and those who use it are not governed by the same rules and / or use the same infrastructure as the NRBE. .
Product	'Product' refers to the output of the production process. The 'product' is located within the pellet production SES as it is here that it is produced. There may be demand for the product within the local SES from 'raw material suppliers', 'competing resource users and actors' and 'infrastructure providers'.
Components of the energy supply SES	The energy supply SES features: 'product users and actors' who can have demand for the product, but may also have access and a desire to use an alternative. 'Energy resources' highlight that competition from or availability of other resources as well as ‘infrastructure’ could impact on the demand for the product.
Production process	The production process labels 'raw material' as an 'input', and is closely connected with 'infrastructure', including 'physical infrastructure' (e.g. the processing plant), 'social infrastructure' (e.g. skills, technology and knowledge) and 'governmental infrastructure' (e.g. laws and policies governing operations and demand for product). The 'output' of the production process is the 'product'.
Internal business dynamics	This element has been added within the 'production process' box, as it relates to those involved in the production process.
Multi-tier variables illustrated by layers	The original framework [34] only considers one level or scale of interactions. The amendment accentuates the need to consider multiple 'infrastructure providers',

behind the four main components	'infrastructure' and 'competing resource users and actors'.
Ecological interactions	The consideration of ecological interactions is encouraged by the addition of linkage '14' which shows that the interlinkages between different ecological variables must be considered.
Addition of infrastructure users	As the original framework [34] was only concerned with those who directly use or who facilitate the use of the 'resource', there is no consideration for those who use the same infrastructure as the enterprise but do not compete for raw material. The introduction of linkage '12' and 'infrastructure users' ensures that practitioners consider those who could impact on the availability of infrastructure required by the NRBE.
Infrastructure being split into physical, governmental and social	The framework now differentiates between 'physical', 'governmental' and 'social' infrastructures as the original term 'infrastructure' [34] is considered too broad, and there was concern that practitioners might overlook one of these elements.
Introduction of 'technology' as an external factor	Technology has been added to external social and economic forces as it cannot be classed as either 'social' or ‘economic', and it is an external factor which could significantly impact upon a NRBE (both positivity and negatively).
External biophysical, social, economic and technological factors influencing all components	With a NRBE, biophysical, social, economic and technical factors can affect all components of the SES.

Table 4. Strategies towards the establishment of a resilient pellet industry in South Africa

Aspect	Strategy
Ecological	• Best management practices for the forestry sector in sub-Saharan Africa [58, 59] must be expanded to include management practices specific to the woody-biomass industry (e.g. methods for returning ash to the plantations)
Social	• Educate and incentivise: i) raw material providers to minimise contamination; and ii) society to be aware of and benefit from the various applications of wood pellets • Lobby for policy-makers to develop and enforce legislation which supports the development of the biomass sector (e.g. logistic concessions, renewable obligation rewards, provision of infrastructure, investment subsidies, feed-in tariffs, carbon tax, public-private partnerships to assist with conversion) [12, 59] • Up-skill workforce to have a competent technical level to meet the demands of a developing biomass industry [12, 59] • Up-skill power utility users with technical instruction on the applications of woody-biomass pellets • Continual research into design and building of logistical and transportation equipment, as well as pelleting technology to optimise operations • Be aware of changes in plantation land tenure
Economic	• Investigate ways of securing reliable access to raw material • Ensure that resources are available to continually investigate logistical optimisation • Ideally raw material, pellet production and end users should be in close proximity to one another to minimise logistic limitations – thus prioritise local markets • Prepare and manage for natural disasters • Do not over commit and fail to meet orders, and have agreements with other plants which are located outside the same SES as the pellet plant to supply pellets during times of poor production • Establish a broad consumer-base and continually explore alternative markets and pellet applications

Figure 1. Woody-biomass production process

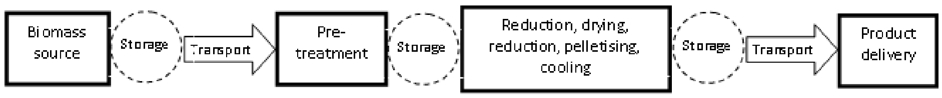
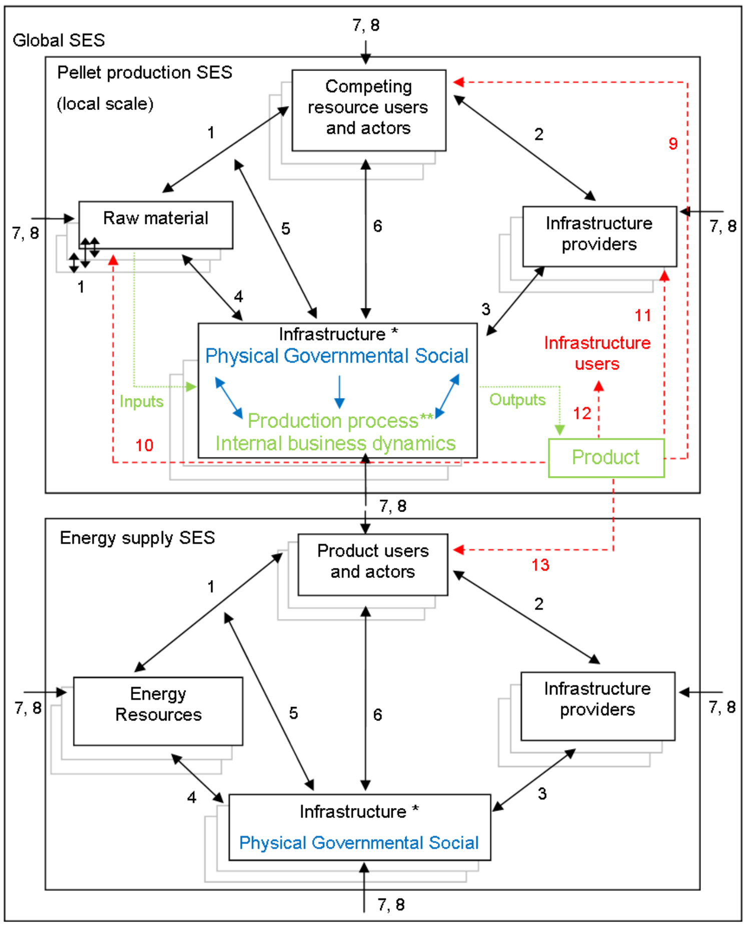


Figure 2. The South African woody-biomass social-ecological system framework. * Physical - transformation and communication infrastructure; governmental – legal and regulatory infrastructure; social – knowledge and skills infrastructure. ** Production process – input of raw material, pre-treatment and pelletising, delivery of product (output). Refer to Table 2 for definitions of the different interlinkages



Supplement 1. Potential ecological, social and economic benefits attributed to the use of woody-biomass

Aspect	Benefit
Ecological	• Reduced dependency on fossil fuels which in turn reduces the emission of harmful gases [1, 2, 3, 4, 5, 6, 7]. Although wood does contain sulphur and nitrogen, which yield SO^2 and NO_x when combusted, the rate of emissions is significantly lower than that of coal [4] • Pellets are carbon neutral [4, 8, 9]. As trees store carbon as a result of photosynthesis, there is no net production of carbon dioxide, The CO_2 generated during combustion of the wood equals the CO_2 consumed during the lifecycle of the tree [4] • The raw material is renewable, and thus can be continuously replenished and reliably supplied [4] provided that the soil nutrients supporting production are not depleted • Potential to recover waste that would otherwise be disposed of via landfills, incinerated, [4, 10] or left to decay and emit carbon dioxide [11] • Promoting best management practices can enable biomass harvesting to be used as a tool for ecosystem restoration [12] • More intensive harvesting can be beneficial for natural regeneration The survival rate of pine seedlings from natural regeneration is enhanced by slash and stump removal after the final harvest, due to improved soil conditions [3] • Short-rotation woody crops can provide a more desirable habitat for forest species than agricultural fields, especially when these new stands have a diversity of tree species, age, and growth habits [13] • The removal of forest waste and the retaining of twig and leaf matting (known as loess) can increase soil fertility [12] and biodiversity when intensively farmed crop lands are converted to forest [13] • Soil organisms can benefit from reduced tillage under perennial energy crops [14], which usually need fewer pesticides and fertiliser applications than traditional agricultural crops [13, 14] • Reducing the potential of forest fires through the removal of thinnings and forest waste [15]
Social	• Job creation throughout the supply chain and ancillary services industry, as well as for farm and forestry workers [9, 10, 12, 16], many of whom currently face economic hardship [4, 11, 17, 18, 19]. Existing jobs would be more secure in the biomass sector, as more manpower would be needed to grow, harvest and manage raw material [18] • The fuel can be burnt cleanly and safely, if properly prepared and used in efficient appliances [18, 20, 21] • Pellets are used in the same way as coal and wood, thus users are familiar with operating methods [19]
Economic	• The establishment of new industry and markets with the availability of reliable energy [4], will reduce local dependency on the international fuel market [10, 12, 18, 22,] • Value being added to processed wood waste [4] • Helps societies diversity their energy sources by providing local energy for communities and through the potential sale of bioenergy products in the energy market [10] • Can be stored and used on demand, unlike solar and wind [23] • Can be stored for a long time [20], transported over long distances [11, 20], and can open up opportunities for trade in remote areas as it can be transported [19] • Can reduce imports and capitalise on SSA land, labour and climate [19] • Power can be fed into the existing grid [24] • With combustible boilers, biomass is 80% cheaper for maintenance costs compared to coal and heavy oil [25] • For co-firing, present supply chains and infrastructure can be used for coal [20] • Pellet plants can utilise dead timber damaged by fire and disease

Supplement 2. Limitations associated with the use of criteria, indicators and certification use to monitor biomass harvesting, bioenergy production and forest management

Identified limitations
1. Instructions on use are frequently omitted
2. Bias towards data abundant criteria/indicators
3. Deficient data criteria/indicators are overlooked
4. The identification and quantification of social and cultural related criteria/indicators is difficult
5. A need for case study specific criteria/indicators
6. Time consuming to collect relevant data
7. Thresholds can be difficult to define
8. Impacts may vary in terms of time and space
9. Identification of universally applicable and understood indicators is challenging

Supplement 3. Woody-biomass risk assessment showing potential risks and associated mitigation measures

Questions	Potential risks	Mitigation measures
Pellet production SES		
Relationship between competing resource users/actors		
• Identify conflicts between competing resource users/actors	• Rural poor, composting (including soil fertility), plastic, cement, fencing and pallet manufacturers. In forestry there are different values and stakeholder preferences which cannot always be understood, interpreted and quantified completely [26], and social and cultural values and opinions can change within short timeframes [27, 28]. Options within stakeholder groups can also vary widely [29]	• Spend time and money on stakeholder consultation [10]. Develop best management practices for planted and hydrologically sensitive areas (where high surface runoff and high potential sedimentation loss are anticipated) (e.g. retain harvesters' off-cuts and organic material for soil productivity and biodiversity [30, 31]. *Investigate production sector mechanisms (e.g. the Forestry Stewardship Council (FSC) certification, which could be used to encourage timber companies to contribute to renewable energy production*
• Identify what advantages the off-take for a pellet plant has over competing resource users/actors	• Minimum raw material preparation required prior to delivery (no separation or sorting of raw material into different sizes is required), whereas there may be financial implications with supplying alternative competing resource users/actors who require uniform sized or type of raw material	• N/A
• Identify what disadvantages the off-take for a pellet plant has over competing resource users/actors	• If raw material is contaminated (e.g. treated with creosote), the pellet plant will reject the material	• Pellet plant to oversee harvesting, processing and housekeeping at source
Relationship between competing resource users/actors and the raw material suppliers		
• Is there sufficient raw material to supply the production process?	• Unlikely, as the pellet plant intends to meet both local and non-local demand	• *Pellet plant to obtain raw material from numerous suppliers to spread risk of losing suppliers*
• *Is the source of raw material reliable?*	• *As suppliers are opposed to committing to long-term contracts, due to an awareness that wood waste could gain in value, it is not possible to confirm a long-term reliable source of material*	• *Be consistent on collections, as often enterprises which pay for wood waste are not long-term. Purchase round-wood and / or plantations*
• Are there other sources of raw material for pellet production?	• There is an abundance of round-wood available from private timber growers. However, the pellet plants will compete with the commercial market for this resource	• *Seek local markets to achieve higher returns, which will enable the plant to compete with commercial buyers for the round-wood*
• Is the available raw material consistently suitable for production?	• As material comes from a variety of different sources, there can be variations in the quality of pellets [10].The pellet plant can take all types of raw material, except treated wood	• Consider forest productivity, including site conditions, soil characteristics, harvesting methods, vegetative cover, and management

		history [32, 33] when securing supply • Educate suppliers on what is classified as treated wood
• Is the plant optimally located for logistics?	• Ever-changing fuel prices and biomass being spread over large areas [10] contribute to uncertainties of profit	• Consider a series of different configurations and improvements in logistics, when deciding on plant location [20, 10]
• Is the source of raw material sustainable?	• Possible degradation of forests and soil fertility, and reduced water availability [34], and thus ecosystem services, as a result of increased planting, harvesting and removal of residue [35]. Possible reduction in water quality due to increased soil and vehicle movement	• A balance is needed between conservation and plantations, and must be based on the principles of ecosystem management [12, 36, 37] • Policies to protect the environment from potential mismanagement due to growth of bioenergy sector must be developed [38] • Combustion residue (oxides) to be returned to plantation soils
Relationship between infrastructure and competing resource users/actors		
• Is there sufficient infrastructure in place to access the raw material and deliver the product?	• Some areas maybe inaccessible, due to weather conditions or a lack of linear or fluvial infrastructure	• Upgrade existing or build new transportation infrastructure to access material and deliver product. Investigate public and private funding sources as the improved infrastructure may not only benefit the pellet industry
• Is there policy / legislation in place to promote and support pelleting as opposed to other raw material uses?	• In the developed world legislation which stipulates that biomass must be used for combustion to produce power to reduce emissions is in place, however this legislation is absent in South Africa. The biomass sector is neglected and poorly governed [19]. Policies that regulate the market are often in conflict, are unrealistic or ineffective, partly due to the biomass energy being governed by different sectors, ministries and agencies, and reliable statistical data are generally not available [39]. Policy implementation is also usually influenced by economics	• Policy-makers to develop and enforce legislation which supports the development of the biomass sector to provide local power
Relationship between infrastructure and raw material suppliers		
• *Are there procedures in place to ensure that the risk of organic and non-organic contamination is minimised?*	• *Often the origin of the wood waste is unknown to the plant prior to its arrival. Thus there may be high levels of silica, and thus organic contamination in the biomass. Poor housekeeping and high staff turnover can lead to non-organic contamination of biomass*	• *Plant management to oversee harvesting process and housekeeping of raw material suppliers*
• Is there sufficient technical knowledge to plan, operate and execute the procurement of raw material?	• No, not specific to South African conditions. Knowledge is deficient on harvesting techniques, raw material handling, climatic conditions, labour force, growing time and biomass composition as South African conditions are unique	• Funding to be channelled towards research on unique South African conditions
• Is there the correct type of equipment to	• There is a lack of specifically designed equipment for the transportation	• Funding to be channelled towards the design

effect the procurement and delivery of raw material?	and handling of biomass in South Africa	and building of logistical and transportation equipment [12]
• Is there legislation / best practice guidelines on forestry and agricultural management?	• Although legislation and management guidelines exist, frequently they are outdated and inefficient in South Africa	• *Funding to be channelled towards developing legislation and guidelines which are specific to South African conditions*
• Is South African knowledge evolving in line with international best practice?	• No, in South Africa opinion and research is frequently influenced and driven by negative economic influence, or it is simply outdated	• Unbiased funding to be made available to re-educate and enlighten researchers and future generations
• What rules, regulations and legislations govern property rights, national parks and biosphere reserves which could impact on accessibility and growing of raw material [40]?	• Although conservation areas are well demarcated in South Africa, there are vast areas of tribal lands which have no formal (documented) controls. Land ownership disputes are common in rural areas	• Confirm land tenure when securing supply
	• For many catchments in South Africa the limits for plantation forestry have been reached and authorisation of further expansion is unlikely	• *Take into consideration when identifying future supplies that some plantations may not be replanted due to water availability and / or permitting constraints*
• *Is the supply chain operating optimally?*	• *The variables associated with logistics are ever changing and complex*	• *Have a designated logistics expert who continuously assesses and manages logistic variables*
Relationship between the physical, social and governmental infrastructures associated with the pellet production process		
• To what degree is there governmental support for the pellet industry?	• Currently there is no governmental support for the pellet industry as governmental revenue is mostly allocated to developing fossil fuel development	• Lobby for international support from renowned green energy bodies (e.g. WWF) to apply pressure at government level. Lobby for support from international importers to insist on renewable energy being used for manufacturing
• *Are investor interests aligned with the objectives of the pellet plant?*	• *South Africa is frequently seen as a country to exploit, due to widespread corruption.*	• *Introduce checks and balances in shareholding and funding contracts*
• *Has financial provision been made to meet out-of-budget occurrences?*	• *Investors frequently under-fund projects in developing countries due to a lack of enforceable judicial legislation*	• *Full funding, with contingency, must be deposited in an escrow account*
Relationship between infrastructure and raw material dynamics		
• Are there any renewable obligation rewards available to raw material suppliers?	• In the EU and US there are rewards for end-users and methane avoidance to suppliers, however there are currently no rewards for raw material suppliers in South Africa (although FSC could be a mechanism to encourage raw material suppliers to direct wood waste to renewable energy production)	• Lobby at governmental level for the effective implementation of renewable obligation rewards [41]
• Are there any penalties applicable to raw material suppliers that do not dispose of their waste legally?	• Legislation exists for the correct management of waste, however the policing of this legislation is lacking	• Lobby at government level for the effective implementation of waste management controls

Relationship between infrastructure providers and competing resource users/actors		
• *Are there existing and favourable relationships between competing resource users/actors and those responsible for the provision of infrastructure used by the competing resource users/actors?*	• *There is potential for some government departments to favour some industries over others (e.g. a municipality may prefer a poultry farm over a sawmill, as poultry pays higher municipal rates compared to sawmilling operations).Corruption within the government may also influence resource user/actor preference (e.g. government officials having private business ventures which benefit from certain industries)*	• *Ensure that infrastructure providers are educated on the direct and indirect benefits of renewable energy, and blow the whistle on corrupt government officials*
Relationship between infrastructure providers and infrastructure		
• *What infrastructure is available and to what extent is it developed, maintained and useable?*	• *Roads are available is some areas; however they are frequently not maintained. High fuel price has a negative impact on profitability and could account for 50% of the total delivery cost [42]. Traffic congestion slows turnaround times on deliveries. Extensive railway line infrastructure exists in some areas, however it is not maintained. There is also insufficient and ill maintained railway rolling stock. Diversion of electrical power from electrified sections to the main grid causes railway delays. Harbours are over burdened, lack loading and storage facilities, and have high harbour and stevedoring tariff rates [20]*	• *Lobby at government level for logistic concessions [43]. Pellet plant to own and operate transport. Focus on local market which reduces transportation costs. Pellet plant to utilise its own power. Return loads to be utilised*
• Are there sufficient skills at government level to ensure the provision and maintenance of the required infrastructure for the pellet plant?	• There is a lack of knowledge, capacity and organisation at government level to ensure the provision of infrastructure. Government discourages the transition from traditional fossil fuels to biomass, as their self-financial interest is in fossil fuels, due to a well-established mining sector	• International environmental pressure and importers of South African goods to insist that a healthy percentage of renewable energy be used in production, instead of fossil fuels
• Are there sufficient skills and knowledge in the private sector to establish and maintain a pellet plant, including all ancillary services?	• A full suite of skills is available for the establishment and operation of a pellet plant in South Africa, however these specialised skills have been honed by only a small nucleus of individuals	• The pellet sector must up-skill to a competent technical level to meet the demands of the developing biomass industry
• Are there sufficient skills and knowledge to retrofit traditional fossil fuel boilers / furnaces to accept biomass?	• Limited technical knowledge is currently available. However the necessity to find solutions is rising due to ever increasing cost of electricity and environmental awareness	• The pellet sector must provide technical instruction to up-skill power utility users
Relationship between infrastructure providers		
• Is there a weak link in the supply chain which impedes on delivery to end user?	• The fragile and erratic service delivery of public infrastructure creates bottlenecks in the supply and delivery of product	• Raw material, pellet production and end users should be in close proximity to one another to minimise logistic limitations
Relationship between external biophysical forces and infrastructure providers, infrastructure and raw material		
• *To what degree are the infrastructure providers prepared for anticipated external biophysical forces?*	• *Preparedness for biophysical events varies amongst public and private sectors and localities*	• *Both the public and private providers must have funds available to be prepared for and manager unforeseen biophysical events*
• What infrastructure could be impacted upon by an external biophysical force?	• Heavy rainfall can inhibit access to raw material and delivery of product to end user	• Maintain access routes

• What natural occurrences could affect or enhance procurement of raw material and production?	• Excessive rainfall could i) hinder harvesting, and thus reduce the availability of timber for sawmilling, which in turn will reduce the availability of sawdust and off-cuts for bioenergy; ii) increase the moisture content of raw material which would increase production costs which in turn will impact on profitability; and iii) increase silica contamination which in turn increases production and maintenance costs. Drought will impede agricultural production, and thus limit available residue. Although trees killed by fire can be used in pellet production, in the long term fires will impact negatively on the viability of the timber industry	• Irrigation could be used to promote growth during drought [43] in catchments with surplus water. Oversee all aspects of the biomass supply chain, especially agricultural and forestry management [10]. Consider utilising more advanced technologies [10]
Relationship between economic forces and infrastructure providers, infrastructure and raw material		
• What external social, technical and economic forces could impact on infrastructure providers and the availability of infrastructure and raw material?	• Public opinion is that biomass is viewed as a fuel of the past – how to change public opinion [19] • Hard to predict profitability due to variable exchange rates [10] • High bank interest rate has negative influence on the purchasing of capital equipment, which in turn has a negative impact on profitability. This is not attractive to investors	• Educate users on the modernity of using pellets as opposed to fossil fuels • *Take out forward cover insurance on transactions. Selling to a local market* • Where possible, pay upfront for equipment
Demand for product Demand from: • Raw material suppliers • Competing resource users/actors • Infrastructure providers • Infrastructure users within the pellet production SES • Energy supply SES	• Markets can become unstable [44] • Those interested will search for information to help them in their decision to convert to pellets. If information does not exist, is difficult to find or is deficient, the change to pellets will not be made [41] • High cost of converting to pellets and lack of a well-developed commercial strategy for biomass [41] and knowledge about the benefits of pellets compared to conventional products [47]. This is complex; fuel-price itself may not be the deciding factor [47] • With increasing market demand for pellets comes an increasing need to secure sustainable supply of raw material [51]. Changes in consumer demand are beyond the control of the producer. Policy measures	• Market incentives, reliable support from financial institutions and be prepared for times of instability [45] (e.g. contingency plans for times of instability • Effective information tools designed to influence consumer behaviour by persuasion, communication and knowledge transfer is recommended [46] • Consumers to be given firm incentives to switch to biomass energy. There should be incentives and access to capital to convert to pellets. For example: tax credit in Sweden [48], carbon taxes in Sweden and in Finland [49], quota systems for green certifications in Belgium, investment subsidies and feed-in tariffs in the Netherlands have facilitated biomass energy transition [50]. • Suppliers must endeavour to deliver sustainably sourced pellets in line with market demand [41]. Suppliers must not flood the

	determine large parts of the trade, and unexpected changes in policy can result in rapidly changing trade patterns (e.g. the UK has promoted domestic supply of biomass and restricted subsidies if the imports exceeded certain limits, resulting in almost no trading of pellets into the UK at one time) [20]	market, as surplus product with reduce profitability of the industry. Likewise, a lack of reliable fuel will encourage consumers to move to an alternative fuel source, which may not be sustainable or environmentally acceptable
	• A lack of logistic infrastructure	• Both exporting and importing countries are required to have infrastructure which enables the product to move from the plant to the consumer [20]
Energy supply SES		
Relationship between alternative energy resources and product users/actors		
• What alternative energy resources (including competing pellet suppliers) are available to the product users/actors and to what degree are these energy resources likely to be used?	• The establishment of new plants in close proximity to existing markets can create a threat to current suppliers	• Establish smaller plants close to raw material and potential markets (plants to be 50% smaller compared to the failed plants, as logistic costs are 50% of operational costs). Have a broad consumer base. Develop markets for alternative applications
	• Solar and wind can supplement current demand for pellets, however they are unable to meet a 24/7 energy demand	• Continuous exploration of alternative markets and applications
	• Conversion back to fossil fuels if pellet suppliers cannot meet demand	• Have alternative arrangements in place should orders not be able to be fulfilled (e.g. have agreements with other plants to supply pellets during times of poor production, breakdowns, lack of raw material)
Relationship between product users/actors and infrastructure providers		
• How could infrastructure providers influence the use of pellets by product users/actors?	• Legislators can: i) be influenced by incentives from fossil fuel suppliers to prioritise the use of fossil fuels; and ii) increase tariffs that would jeopardise the feasibility of producers to make export less feasible	• Development of local markets and applications. Public lobbying to encourage the use of renewables. Development of local markets close to raw material and plant. Encourage production sector initiatives to promote more sustainable production (e.g. through mechanisms such as FSC)
Relationship between infrastructure and alternative energy resource dynamics		
• What infrastructure can influence the use of alternative energy resources dynamics?	• A lack of transportation network and power can hinder pellet logistics and production, thus users are forced to use alternative energy sources	• Establish plants in close proximity to raw material and markets
	• Misinformed policy makers have the potential to favour non-combustible renewables	• Implement strategies to educate policy-makers

Relationship between product users/actors and infrastructure		
• What infrastructure is required to ensure that product users/actors receive pellets timeously?	• Lack of transportation network maintenance and increased congestion of logistics (e.g. trucking delays at harbour)	• Establish smaller plants close to market and raw material
Relationship between external biophysical forces and alternative energy resources and infrastructure		
• What external biophysical forces can affect the use of alternative energy resources?	• A lack of raw material (e.g. due to flooding and thus inaccessibility of material) can result in product demand not being met. This in turn will likely result in product users/actors turning to alternative energy resources	• Develop agreements with other plants which are located outside the same SES as the pellet plant to supply pellets during times of poor production
• What external biophysical forces could impact on the infrastructure required to deliver product to product users/actors?	• Extreme weather events could hamper product delivery	• Stockpile product for when supply cannot meet demand
Relationship between external social and economic forces and infrastructure providers, infrastructure and alternative energy resources		
• What external social, economic and technological forces could impact on infrastructure providers, infrastructure and alternative energy resources?	• War, conflict, famine could reduce the demand for pellets • Recession and government budget allocations could affect the availability of funds for infrastructure provision • Investor interest and preference for pellets, to an alternative energy resource, may be influenced by conflict, change in government (e.g. threat of privatisation of plant may cause investors to lose confidence in the long-term availability of pellets)	• Establish a broad consumer base • Establish a broad consumer base. Develop markets for alternative applications • Develop agreements with other plants which are located outside the same SES as the pellet plant to supply pellets, should the plant cease to function