Master's Thesis – master Energy Science

Residues to the Rescue

An assessment of the GHG and cost performance of sugarcane residues for bioenergy: a case study for Peru

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Executive summary

In the Netherlands, co-firing wood pellets in originally coal-fired power plants is a common pathway for meeting renewable energy targets. The expected growth in demand for wood pellets for high-value applications (e.g. bio-based products) has resulted in an increased exploration of the energy potential of agricultural residues. Research indicates that pellets made from sugarcane bagasse have potential to be a cost-effective biomass fuel for co-fired power plants. However, the availability of bagasse for export could be limited if all produced bagasse is employed locally in the boiler of the sugarcane mill for energy purposes. Sugarcane straw could be supplied to the boiler at the sugarcane mill to replace bagasse. This way of 'freeing up' bagasse could increase the export potential of bagasse.

Biomass for electricity and heat generation needs to comply with GHG emission reduction criteria. In the Netherlands, a minimum of 70% GHG savings compared to the fossil alternative needs to be obtained. In order to assess the potential of bagasse pellets, the following research question is addressed: *How does a bagasse pellet supply chain with end-use in a power plant in the Netherlands perform in terms of GHG emissions and costs?* The Amer Bio CHP in the Netherlands is assumed as end-using facility. Peru is selected as a case study for bagasse supply since this country shows a significant unused energy potential of sugarcane residues. The potential bagasse supply is assessed in three scenarios: 1) surplus bagasse (SB), 2) surplus bagasse and freed up bagasse by implementing improvements at the sugarcane mill (FBI) and 3) surplus bagasse, freed up bagasse from improvements and freed up bagasse by using straw in the boiler of the sugarcane mill (FBS). The GHG emissions are calculated to determine whether bagasse pellets comply with GHG targets. The bagasse pellet costs are calculated to evaluate the cost-effectiveness compared to wood pellets. Also, the alternative of using straw locally for bioelectricity generation is assessed to determine its economic feasibility. A combination of spatial analyses, consultations of literature and national reports and personal communication with experts is used in the methodology of this research.

The results in GHG emissions and bagasse pellet costs in the SB and FBS scenario from the region Piura are depicted in Figure E1. The results of the FBI scenario are similar to the SB scenario and therefore not shown. The major contributing stages to the supply chain GHG emissions consist of straw collection (for the FBS scenario), pre-treatment, deep-sea shipping and end-use. Bagasse pellets in FBS show significantly higher GHG emissions as a result of emissions from the collection and transport of straw to the sugarcane mill for freeing up bagasse. Figure E1 depicts the maximum allowable GHG emissions of 23.1 gCO_{2eq} per MJ pellet in order to comply with the Dutch GHG target of 70% GHG savings. It can be observed that the bagasse pellets in both scenarios amply comply with this target. Also, the maximum allowable GHG emissions of 15.4 gCO_{2eq} per MJ pellet in order to comply with 80% GHG savings, as set by the RED II, are depicted. This target is currently only relevant if bagasse pellets would be used in other installations for electricity and heat generation starting operations from 2026. Complying with this target becomes more challenging, especially when straw is used for freeing up bagasse (represented by the FBS scenario). One of the uncertainties assessed in the sensitivity analysis is the inclusion of potential (negative) GHG emissions from soil carbon stock changes, as a result of improved agricultural management and land-use change. It is found that, depending on the assumed reference situation, the inclusion of these emissions has a major impact on the obtained GHG savings. Nevertheless, even in the assessed worst case scenario, the bagasse pellets are still expected to comply with the Dutch GHG target.



Figure E1. Bagasse pellet GHG emissions and costs for the region Piura.

A breakdown of each stage of the bagasse pellet supply chain is depicted. Stages indicating 'costs' in brackets only apply for the supply chain costs.

From Figure E1, it can be observed that the major contributing stages to the supply chain costs are surplus bagasse collection, straw collection for freeing up bagasse (in FBS), pre-treatment and deepsea shipping. Figure E2 depicts the cost-supply curves of the potential bagasse pellet supply from the three assessed regions in Peru. The curves show the pellet supply in the subsequent scenarios SB, FBI and FBS and the respective average bagasse pellet costs in these scenarios. Bagasse pellets from La Libertad show the highest supply potential at the lowest costs. Bagasse pellet costs in FBI are slightly higher than SB due to required investments for improvements at the sugarcane mill. A significant increase in costs is notable in FBS as a result of costs for straw collection and transport. A maximum allowable cost range of $8.5-9.4 \notin/GJ$, based on average industrial wood pellet prices, is assumed to determine the economic potential of bagasse pellets. This cost range is depicted in both Figures E1 and E2. It is found that the bagasse pellet costs remain within the allowable cost range and are even lower than the lower cost limit in the SB and FBI scenarios. The economic potential below the lower cost limit, represented by bagasse pellets produced from surplus bagasse and freed up bagasse by improvements at the sugarcane mill, amounts to 6 PJ/y (402 ktonne/y). The additional economic potential when straw is used for freeing up bagasse amounts to 2.9 PJ/y (196 ktonne/y).

As an alternative use of straw, the levelised costs of energy (LCOE) of local bioelectricity generation at the sugarcane mill from straw is calculated to determine its economic feasibility. The results show a range in LCOE of 68-112 €/MWh. Considering the bioelectricity cut-off price in Peru of 52 €/MWh, it can be stated that this option is not economically feasible. Especially for Peru where electricity from other renewables can be generated at lower costs and where hydropower already has a significant share in the national electricity mix of 55.1%, it is not expected that straw for bioelectricity will become competitive with other renewables in the future. Therefore, there is no economically feasible business case for the local use of straw for bioelectricity generation in Peru.



Figure E2. Cost-supply curve of bagasse pellets up to delivery at the Amer Bio CHP.

This research shows that bagasse pellets from Peru have much potential as biomass fuel for electricity and heat generation in an existing power plant in the Netherlands and can be competitive with wood pellets, considering the GHG and cost performance. Moreover, bagasse pellets show considerable potential for substituting wood pellets since the use of woody biomass for bioenergy is currently heavily debated in the Netherlands. Using pellets made from sugarcane residues for electricity and heat generation could be more socially accepted than the use of wood pellets. The role of bagasse pellets in the Netherlands is, however, expected to gradually shift to applications in the bio-based products sector in the near future. This is a result of national policy towards a bio-based economy in which there is decreasing support of biomass for electricity and heat generation and increasing support of biomass for high-value applications. The mobilisation of sugarcane residues for the bagasse pellet supply chain has the potential to stimulate local initiatives in Peru for developing a bio-based products sector. The setup of the bagasse pellet supply chain could therefore contribute to the development of a bio-based economy in Peru in the long run.

Future research should focus on factors for mobilising sugarcane residues in Peru, such as the amount of straw that should remain on the field for agro-ecological purposes and the potentials for freeing up bagasse at the sugarcane mills. Also, this research indicates that bagasse sourced from Peru shows many potentials for end-use in the Netherlands for bioenergy purposes. It is therefore recommended to companies with a demand for bagasse to approach Peruvian sugarcane mill operators for collaborations and for setting up pilots. Finally, policymakers in the Netherlands are recommended to compose a biomass strategy, in which criteria for ensuring biomass sustainability and efforts to foster developments towards a bio-based economy should be well-balanced.

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Acronyms and abbreviations

Amer	Amer Bio CHP
Bagasse	Sugarcane bagasse
CAPEX	Capital expenditures
CH ₄	Methane
СНР	Combined heat and power
CO ₂	Carbon dioxide
CO _{2eq}	Caron dioxide equivalents
DWT	Deadweight tonnage
EC	European Commission
EU	European Union
FAO	Food and Agricultural Organization
FBI	Scenario for bagasse supply potential, assuming surplus bagasse and freed up
	bagasse from improvements at the sugarcane mill
FBS	Scenario for bagasse supply potential, assuming surplus bagasse, freed up bagasse
	from improvements and freed up bagasse from using straw in the boiler
FCI	Fixed capital investments
GHG	Greenhouse gas
GIS	Geographic information system
GWP	Global warming potential
HFO	Heavy fuel oil
kWh	Kilowatt-hour
LCA	Life cycle assessment
LCOE	Levelised costs of energy
LHV	Lower heating value
MC	Moisture content
MDO	Marine diesel oil
MINAGRI	Ministerio de Agricultura y Riego
MINEM	Ministerio de Energía y Minas
MTC	Ministerio de Transportes y Comunicaciones
MWh	Megawatt-hour
N ₂ O	Nitrous oxide
OPEX	Operational expenditures
RED	Renewable Energy Directive
RWE	RWE Generation NL
SB	Scenario for bagasse supply potential, assuming surplus bagasse
SC70	Scenario for local bioelectricity generation from straw, assuming 70% of sugarcane
	fields are harvested mechanically
SC100	Scenario for local bioelectricity generation from straw, assuming 100% of sugarcane
	fields are harvested mechanically
SER	Sociaal-Economische Raad
Straw	Sugarcane straw
U.S.	United States
USDA	United States Department of Agriculture
WUR	Wageningen University & Research
wt%	Weight percentage

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1 Introduction

In order to meet renewable energy targets, the use of woody biomass in co-fired power plants for electricity and heat generation has increased in several countries in the European Union (EU) (Roni et al., 2017). Electricity and heat generation from biomass in EU countries must comply with greenhouse gas (GHG) emission reduction criteria as set in the Renewable Energy Directive (RED) II (European Commission (EC), 2018c). The RED II requires a minimum of 70% GHG savings compared to the fossil alternative for installations starting operations from 2021 onwards, increasing to 80% GHG savings for installations starting operation from biomass to meet a minimum of 70% GHG savings from 2018 onwards (Staatscourant, 2017). This criterium also holds for facilities that are already in operation.

The Netherlands currently has four operating power plants in which coal and biomass are co-fired. The Amer Bio CHP (further referred to as 'Amer'), operated by RWE Generation NL (further referred to as 'RWE'), is one of these plants where biomass is currently co-fired for the cogeneration of electricity and heat. The demand for biomass fuel is expected to increase as coal is gradually being phased out, as a consequence of the prohibition of coal use for electricity generation from 2025 onwards (RWE, 2019; Staatsblad, 2019). Whereas mainly white wood pellets are currently used as biomass fuel for electricity and heat generation, the demand for woody biomass is expected to increase in the coming decades for high-value applications, such as the production of bio-based products (EC, 2018a; Sociaal-Economische Raad (SER), 2020). Continuing technological advances in this sector will increase demand for woody biomass fuels on a global scale (Lamers et al., 2014; Thrän et al., 2017; Yang et al., 2013). Due to the rising demand for woody biomass and subsequently, the rising pressure on the availability of woody biomass resources, increased attention is given to the potential of lower-quality biomass for electricity and heat generation (Garcia et al., 2016; Walter et al., 2014). Agricultural residues are an example of such lower-quality biomass, among which sugarcane residues attract much attention (Seabra & Macedo, 2011).

Walter et al. (2014) found that pellets made from sugarcane bagasse (abbreviated to 'bagasse'), a byproduct of crushing sugarcane stalks at the sugarcane mill, have potential to be an adequate and costeffective alternative for wood pellets. Research has been conducted on the supply chain of bagasse pellets with end-use in the Netherlands, e.g. by Mai-Moulin et al. (2017) and Vera et al. (2019). Mai-Moulin et al. (2017) assessed the export potential of bagasse pellets from Sao Paulo (Brazil) for electricity and heat generation in the Netherlands. While the supply chain complies with GHG emission reduction criteria, the costs were estimated to be rather high due to relatively long domestic and intercontinental transport distances. To decrease domestic supply chain costs, it would be effective to investigate supply chains with shorter domestic transport distances.

The export potential of bagasse could, however, be limited if the local demand for bagasse is high. Nowadays, bagasse is employed in the boilers of the sugarcane mill to generate heat and electricity for processes in the sugarcane mill (Carpio & de Souza, 2017; Mai-Moulin et al., 2017). A rising number of sugarcane mills also uses bagasse to generate surplus electricity which is supplied to the national grid. As sugarcane mill operators increasingly invest in improved equipment in the sugarcane mill to increase surplus electricity generation, the local demand for bagasse is rising (Mai-Moulin et al., 2017), leaving no unused (or surplus) bagasse available for third party uses.

On the other hand, the availability of sugarcane residues has increased as a consequence of abandoning the traditional pre-harvest burning practice of sugarcane fields, which induced a transition to mechanised harvesting (Cardoso et al., 2015). This has resulted in increasing volumes of produced bagasse at the sugarcane mill and increasing volumes of sugarcane straw (abbreviated to

'straw') left on the field. The growing availability of straw has induced research on the possibility for generating surplus electricity at the sugarcane mill by using straw in existing boilers (Cervi et al., 2019a; Menandro et al., 2017). However, investments in e.g. larger boilers and a connection to the national grid are often required in traditional sugarcane mills (Cervi et al., 2019b). Moreover, the different chemical composition of straw compared to bagasse may cause technical difficulties, such as corrosion and the slagging of ashes, when large volumes of straw are combusted in originally bagasse-fired boilers (Leal et al., 2013). Alternatively, considering the value of bagasse for third parties, straw could be applied in the boilers of sugarcane mills in rather limited amounts to replace a share of the bagasse supplied to the boiler. This way, bagasse could subsequently be sold to third parties.

From the review above, it becomes clear that pellets from bagasse have potential to be a suitable biomass fuel for co-fired power plants. RWE is already exploring the technical potential of bagasse pellets in the Amer in small and larger-scale tests (Agro&Chemie, 2020). The availability of bagasse is, however, limited by the local demand for bagasse. Availability could be increased when straw is used in the boiler for freeing up bagasse, which is a possibility if there is no further incentive for the local use of straw (e.g. for surplus electricity generation). Although the bagasse pellet supply chain with end-use in the Netherlands and the use of straw for local bioelectricity generation have already been studied, the potentials have only been addressed individually in literature. An integrative bagasse pellet supply chain that considers the use of straw for freeing up bagasse has not yet been studied before.

This study aims to analyse the potential of a bagasse pellet supply chain with end-use in a power plant in the Netherlands, considering the supply of surplus bagasse and bagasse that is freed up from the boiler at the sugarcane mill. The Amer is assumed as the end-use facility. The potential of the supply chain is assessed in terms of 1) GHG performance, to determine if the bagasse pellets comply with GHG emission reduction criteria, and 2) cost performance, to determine the cost-effectiveness of bagasse pellets compared to alternative fuels. The following research question is addressed:

How does a bagasse pellet supply chain with end-use in a power plant in the Netherlands perform in terms of GHG emissions and costs?

The following sub-questions are formulated:

- What is the sustainable technical potential of bagasse and straw?
- What is the optimal location of a pre-treatment plant for the pelletisation of bagasse, in order to optimise supply chain GHG emissions and costs?
- What is the economic supply potential of bagasse pellets from the sourcing country?
- How do the bagasse pellets perform compared to alternative fuels?
- Is the local use of straw for bioelectricity generation economically feasible?

Peru is selected as a case study because of its remarkable sugarcane yields due to the favourable climate in the coastal area (Food and Agricultural Organization (FAO), 2020; Marcelo et al., 2017). Assureira and Assureira (2013) found a significant unused energy potential of 3.1 Mtonne (22 PJ) bagasse and 1.9 Mtonne (25 PJ) straw per year in Peru. Since sugarcane mills are located along the coast (Marcelo et al., 2017), domestic transport distances to an export port are potentially low, resulting in low domestic transport GHG emissions and costs. This could, however, be counterbalanced by the relatively long ocean distance from Peru to the Netherlands. In summary, Peru shows potential for the bagasse pellet supply chain, but it is important to analyse the entire supply chain to evaluate its performance. The potential bagasse supply from Peru is determined based

on the current situation and the expected availability for the coming years. Hence, a time horizon from today until ten years from now is assumed in this research.

This study contributes to literature by providing outcomes on the potential of a bagasse pellet supply chain for the specific case study of Peru, in terms of GHG and cost performance. Furthermore, this research analyses the potentials for freeing up bagasse by using straw in the boiler of the sugarcane mill. This integration of straw-enabled bagasse supply for export has not yet been addressed in literature. The outcomes therefore provide new insights in the potentials of freeing up bagasse, considering the contribution of this procedure to the bagasse supply and its impact on the bagasse pellet GHG and cost performance. Finally, the results of this study contribute to the relatively new subject of the economic feasibility of straw for local bioelectricity generation, specified for the case study of Peru.

Besides the scientific relevance, the outcomes of this study indicate whether bagasse pellets from Peru comply with GHG emission reduction criteria and could therefore be used for electricity and heat generation in the Netherlands. Additionally, the results indicate whether the bagasse pellets are cost-competitive with wood pellets and could potentially replace wood pellets for electricity and heat generation. This is relevant since the use of woody biomass for bioenergy is currently heavily debated in the Netherlands (Strengers & Elzenga, 2020). Bioenergy from bagasse pellets could be more socially accepted as these pellets are produced from agricultural residues. Furthermore, the outcomes of this study are valuable for alternative end-use facilities in the Netherlands, such as for the bio-based products sector. Bagasse pellets from Peru could contribute to meeting the expected growing demand for biomass by this sector. Finally, the mobilisation of sugarcane residues for the bagasse pellet supply chain provides opportunities for Peru by stimulating local developments and economic activity.

This report is structured as follows. Section 2 elaborates on the theoretical background of the research. The research method is provided in section 3 and the results of the research are presented in section 4. Section 5 provides a discussion of the results and their implications. The report is finalised with a conclusion in section 6.

2 Theoretical background

This section elaborates on the theoretical background of the research. First, theory on sugarcane residues and biomass potentials is provided. This is followed by an elaboration on conducting a biomass supply chain and geospatial analysis. Then, environmental aspects are highlighted considering the lifecycle assessment and GHG performance of a biomass supply chain. Finally, the biomass supply chain costs and levelised costs of energy are discussed.

2.1 Sugarcane residues

Sugarcane bagasse and straw are retrieved from sugarcane, a crop used for sugar and ethanol production (Bajay, 2011). Bagasse is retrieved at the sugarcane mill after crushing sugarcane stalks and is used to generate steam and optionally electricity in a cogeneration system for meeting the energy demand of processes in the sugarcane mill. Moreover, bagasse is becoming increasingly important to sugarcane mill operators for surplus electricity generation (Bajay, 2011). During the last decades, sugarcane mill operators (especially in Brazil) have invested in technological improvements and optimisation of processes in the sugarcane mill to decrease energy demand and increase surplus electricity generation (Bajay, 2011; Dias et al., 2011; Dos Santos & Ramos, 2020).

Besides the conventional use of bagasse for steam and electricity generation, the use of bagasse for other purposes is gaining more attention. Whereas the paper and pulp industry has a relatively small demand for bagasse (Hofsetz & Silva, 2012), more research is currently conducted on the conversion of bagasse to second generation biofuels or bio-based products in lignocellulosic-based biorefineries (Carpio & De Souza, 2017; Santos et al., 2016). As the technological advances of bagasse as feedstock for biorefineries continue, it is expected that demand for bagasse for the production of bio-based products will expand significantly in the coming decades (Santos et al., 2016).

Straw consists of green tops, green leaves and brown leaves (Seabra et al., 2010). The use of straw has gained increasing attention in literature during the last decade. The traditional practice of preharvest burning sugarcane fields to facilitate manual harvest procedures is being prohibited in an increasing number of countries due to environmental reasons (Leal et al., 2013). Manual harvest practices are consequently being replaced by mechanical harvest equipment. With the mechanical harvest of sugarcane, straw is separated and deposited on the field (Hassuani et al., 2005). Leaving straw on the field has several agro-ecological benefits, such as reduced soil erosion, improved soil carbon stocks, inhibition of weed growth, nutrient recycling and increased soil water retention (Hassuani et al., 2005; Leal et al., 2013). However, leaving straw on the field also has some drawbacks, such as impeded mechanical cultivation and ratoon fertilisation, reduced sugarcane yields and fire hazards during and after harvest (Hassuani et al., 2005). To avoid this, a share of the available straw should be removed and can be used for other purposes, such as for second generation biofuels production or bioelectricity generation (Hassuani et al., 2005; Leal et al., 2013). Straw has occasionally been employed in boilers at the sugarcane mill as a supplement to bagasse to increase surplus electricity generation (Cervi et al., 2019a). Straw could be combusted in the existing bagasse-fired boiler at the sugarcane mill, however, the higher chlorine and potassium content in straw may cause technical problems in the boiler such as corrosion, deposits on hot surfaces and the slagging of ashes (Leal et al., 2013). Using a mixture of bagasse and straw rather than combusting only straw could be a solution to overcome these technical problems (Cervi et al., 2019b). Investments in improved and larger boilers are often required to process the available volumes of straw (Cervi et al., 2019b; Dias et al., 2011).

2.2 Biomass potentials

It is important to identify the biomass potentials when biomass for energy is considered. Four categories of potentials are commonly distinguished: theoretical, technical, economic and implementation potential (Torén et al., 2011). Moreover, a fifth potential is commonly used, which is the sustainable implementation potential. The theoretical potential is the maximum amount of biomass feedstock within its biophysical limits that is theoretically available for bioenergy. Regarding residual biomass, the theoretical potential consists of the total produced amount of residues. The technical potential is defined by the amount that can be extracted with the current technical possibilities. Additionally, limitations in availability due to among others land-use and ecological constraints are taken into account. Then, the share of the technical potential that meets criteria for economic profitability is defined by the economic potential. The implementation potential is the share of the economic potential that can be implemented in a specific socio-political framework and within a certain time frame. Social, economic and institutional limitations and policy incentives are considered in the implementation potential. Finally, the sustainable implementation potential represents the result of integrating environmental, economic and social sustainability criteria in the assessment of biomass resources. Especially the inclusion of sustainability criteria is becoming increasingly important in politics and industry that strive for more sustainable practices in biomass use (Torén et al., 2011).

2.3 Biomass supply chain

According to Hoefnagels et al. (2014), feedstock supply chains are composed of several stages in which the following operations take place: harvest and collection, storage, transportation, pre-processing (or pre-treatment) and handling and queuing. These operations can take place in different order, occurrences and locations, depending on the specific supply chain. General stages of a feedstock supply chain are described next in the following composition and order: harvest and collection, pre-treatment, transport and end-use.

2.3.1 Harvest and collection

A general feedstock supply chain starts with the harvest and/or collection of feedstock. Depending on the type of feedstock, this could for example be at the field site or at a facility where it is collected as a process residue. General processes at the field site for feedstock collection include among others windrowing and baling in the case of herbaceous feedstock or felling, piling, skidding and chipping in the case of trees (Hoefnagels et al., 2014). The processes on the field often require energy input (e.g. diesel for harvest machinery).

2.3.2 Pre-treatment

When the feedstock supply chain involves international long-distance transport, a pre-treatment stage should be introduced early in the supply chain. The bulk and energy density are increased and the moisture content (MC) is decreased during pre-treatment, which are crucial steps for reducing the GHG emissions and costs of subsequent (long-distance) transport stages (Walter et al., 2014). The number of required size and moisture reduction processes in the pre-treatment stage depends on the used raw material (Visser et al., 2020b). General processes include chipping, grinding, drying, conditioning, pelletising and cooling. The size of raw feedstock is reduced in the chipping and grinding steps, which is required before feedstock can be supplied to the dryer. The MC is reduced during the drying processes. Support fuel for heat provision in this process is required. Heat can be supplied by combusting fossil fuels (e.g. natural gas) or biomass fuels. After a subsequent fine grinding step, conditioning of biomass is required to facilitate the binding process during pelletisation and to increase the mechanical durability and moisture resistance of pellets (Thek & Obernberger, 2010). Conditioning involves treatment of dried feedstock with steam, water or biological additives. In the pelletising process, layers of biomass are placed on a die and run over with rollers. At the end of the

pelletising process, pellets have reached a temperature of approximately 80 °C and therefore need to be cooled (De Almeida et al., 2017).

The capital and operational costs of biomass pre-treatment decrease with increasing pre-treatment plant size due to scale economies (Visser et al., 2020b). Pellets are produced in parallel production lines. The required number of production lines depends directly on plant size. Whereas capital scale economies are limited due to this modular design, the plant operator could benefit from discounts when large volumes of equipment are bought. The required labour per unit of produced pellet generally decreases with increasing plant output, since the pelletising process is highly automated and does not require much more labour with increasing production to monitor the automated processes (Visser et al., 2020b).

Important factors to consider when choosing an appropriate location of a pre-treatment plant are the raw feedstock availability and transport distances from the location of feedstock supply to the pre-treatment facility and export terminal (Visser et al., 2020b). Due to scale economies, it is desirable to have large scale pre-treatment plants with a high supply of raw feedstock. At the same time, however, the transport distances and volumes of transported raw feedstock should be considered since these affect the transport GHG emissions and costs of the supply chain. Such factors should be thoroughly investigated in determining the optimal pre-treatment plant location.

When using 'pre-treatment' and 'pellet' in combination with 'stage' or 'plant' in the remainder of the report, this always refers to a facility or the stage in which raw biomass is converted to biomass pellets through the previously explained processes of the pre-treatment stage.

2.3.3 Transport

Supply chains with an overseas-sourced biomass feedstock involve transport stages in the sourcing and destination country and a deep-sea transport stage. The appropriate transport modes used in the sourcing and destination country depend on several factors, such as type of feedstock, transport distances and the existing transport network. Transport of raw feedstock from the collection site to a pre-treatment plant commonly occurs via trucks (Hoefnagels et al., 2014). Trucks are generally preferred for rather short distances (<100 km) due to their relatively low fixed costs. A mix of transport modes (i.e. truck, rail and (barge) ship) could be favourable when transport distances are longer due to their relatively low variable costs, in comparison to the exclusive use of trucks (Hoefnagels et al., 2014).

For international deep-sea shipping, feedstock has to be delivered to an export port with facilities appropriate for handling the specific type of feedstock. Ports can have various terminals that enable the handling of for instance containers, dry bulk or liquid bulk. After storage at the export terminal, the feedstock is shipped with an international deep-sea vessel. The following four vessels for deep-sea transport exist: Handysize (30,000-35,000 deadweight tonnage (DWT)), Handymax or Supramax (40,000-60,000 DWT), Panamax (60,000-75000 DWT) and Capesize (170,000-180,000 DWT) (Hoefnagels et al., 2014). These vessels have multiple compartments which allow the transportation of different types of cargo. Although larger vessels provide economies of scale, the vessel size could limit the access to port terminals or shipping routes. In addition, the vessel ideally carries a full load during the return trip since this is most cost-effective (Visser et al., 2020b). It could become difficult for larger vessels to obtain enough cargo at the destination terminal for a fully loaded return trip. In such cases, a fully loaded smaller vessel could be preferred.

2.3.4 End-use

At the import terminal, feedstock is unloaded and stored or directly transloaded to the appropriate transport mode used for transport to the end-using facility. At the end-using facility, feedstock is unloaded, stored and converted to the desired end product.

2.4 Spatial analysis with ArcGIS

An appropriate tool for carrying out geospatial analyses is a geographic information system (GIS), which has been used in numerous supply chain studies. ArcGIS from Esri¹ is a well-known GIS software which has multiple features that can be used in spatial analyses. For instance, basic measurements can be carried out, such as measuring the direct (as the crow flies) distance between two locations or calculating the area or circumference of an area. In supply chain studies, the measured direct distance between two locations can be used as a representation of the transport distance between two locations that are connected through unpaved roads, e.g. as executed by Cervi et al. (2019b). In reality, the unpaved road could be rather tortuous and the actual transport distance could be longer than the measured direct distance. It is therefore common to correct the direct distance with a tortuosity factor to calculate a realistic transport distance (Monforti et al., 2013). Another functionality is the network analyst feature, which can indicate and measure the shortest distance between locations following existing roads. There are various publicly available databases where road map files of existing roads can be obtained (e.g. OpenStreetMap (n.d.)). The described functionalities are only a few examples of the numerous geospatial functionalities of ArcGIS.

2.5 Life cycle assessment

A life cycle assessment (LCA) is a tool for analysing the environmental burden of a product in all stages of its lifecycle (Guinée & Lindeijer, 2002). Stages of the product lifecycle include the extraction of resources, processing to a product, product use and final disposal. The environmental burdens include all types of effects on the environment, such as emissions of hazardous substances, land-use change and extraction of various resources. Besides an assessment of the entire product lifecycle (cradle-to-grave), partial product LCAs (e.g. cradle-to-gate or gate-to-gate) are also commonly practised in environmental research (Rebitzer et al., 2004).

A generally accepted framework of conducting a LCA² consists of four phases: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment and 4) interpretation. In goal and scope definition, the product system, system boundaries, functional unit and used data categories are defined (Lee & Inaba, 2004). The functional unit is the basis that enables the comparison and analysis of alternative goods or services. In this phase, the necessary allocation procedures should be defined when the system has more than one output. Additionally, the assessed environmental impact categories should be defined, such as global warming potential (GWP)³, human toxicity and acidification. The inventory analysis phase includes data collection and calculations to quantify material and energy flows entering and leaving the system and their environmental loads. All inputs and outputs of the system should be aligned with the functional unit. The impact assessment phase involves the classification, characterisation, normalisation and weighing of the various assessed environmental impacts. This phase is less important if only one environmental impact is studied. The final phase consists of analysing and comparing the results with previous findings. In practice, the interpretation phase occurs after each phase. One could always return to a previous phase if found necessary.

¹ Esri is a global company that builds ArcGIS, a mapping and spatial data analytics software (Esri, n.d.).

² The general framework as proposed by International Standards Organisation (ISO) is based on ISO 14040 (1997), ISO 14041 (1998), ISO 14042 (2000) and SO 14043 (2000).

³ The GWP expresses the contribution of different GHGs to global warming (Bird et al., 2011). This research uses the term GHG emissions instead of GWP.

2.6 Biomass GHG assessment

The RED II provides guidelines for assessing the GHG emissions of a feedstock supply chain in a LCA framework (EC, 2018c). All equations presented in this subsection refer to the methodology provided by the RED II. The GHG emissions from a biomass fuel for electricity and heat generation are calculated with eq. (1). The relevant emission categories that have to be included depend on the studied supply chain. The emissions of carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) must be taken into account and expressed in CO₂ equivalent (CO_{2eq}) emissions. Conversion factors are 1 CH₄ = 25 CO_{2eq} and 1 N₂O = 298 CO_{2eq}. Emissions from fuel use (e_u) only include non-CO₂ emissions, which is in line with assumed CO₂ neutrality of biomass fuel combustion.

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr}$$
 [eq. 1]

Ε	Total emissions from the production of the fuel before energy conversion (gCO _{2eq} /MJ)
e _{ec}	Emissions from the extraction or cultivation of raw materials
el	Annualised emissions from carbon stock changes caused by land-use change
e_p	Emissions from processing (or pre-treatment)
e _{td}	Emissions from transport and distribution
e_u	Emissions from the fuel in use
e _{sca}	Emission savings from soil carbon accumulation through improved agricultural management
e _{ccs}	Emission savings from CO ₂ capture and geological storage
e _{ccr}	Emission savings from CO ₂ capture and replacement

The annualised emissions from changes in carbon stock from land-use change (e_l) are calculated by dividing the total emissions over 20 years. e_l can be calculated as follows:

$$e_l = (CS_R - CS_A) * CF_{CO2,C} * \frac{1}{20} * \frac{1}{P} - e_B$$
 [eq. 2]

 e_l Annualised emissions from carbon stock changes caused by land-use change (gCO2eq/MJ) CS_R Carbon stock per unit area in the reference land-use, measured in carbon mass per unit area CS_A Carbon stock per unit area in the actual land-use, measured in carbon mass per unit area $CF_{CO2,C}$ Conversion of C to CO2 using the molecular weights (respectively 12.01 g/mol and 44.01 g/mol)PAnnual crop productivity, measured as biomass fuel energy per unit area per year e_B Bonus of 29 gCO2eq/MJ if biomass is retrieved from restored degraded land under certain
conditions further defined in the RED II

The GHG emissions for electricity and heat generation in a combined heat and power (CHP) facility can be calculated with eqs. (3) and (4).

$$EC_{el} = \frac{E}{\eta_{el}} \left(\frac{C_{el} * \eta_{el}}{C_{el} * \eta_{el} + C_h * \eta_h} \right)$$

$$EC_h = \frac{E}{\eta_h} \left(\frac{C_h * \eta_h}{C_{el} * \eta_{el} + C_h * \eta_h} \right)$$

$$[eq. 3]$$

EC_{el}, EC_h	Total GHG emissions from respectively electricity (gCO $_{\rm 2eq}/MJ_{e})$ and heat (gCO $_{\rm 2eq}/MJ_{th})$
Ε	Total GHG emissions of biomass fuel before conversion
η_{el}, η_h	Electrical and thermal efficiency respectively
C _{el}	Fraction of exergy in electricity, set to 100%
C_h	Fraction of exergy in useful heat, equal to the Carnot efficiency. If excess heat is below a temperature of 150°C, a Carnot efficiency of 0.3546 can be applied.

Finally, the GHG emission savings of electricity and heat generation from biomass fuels can be calculated with eq. (5). The fossil fuel comparators provided by the RED II are $183 \text{ gCO}_{2eq}/\text{MJ}_e$ for electricity and $80 \text{ gCO}_{2eq}/\text{MJ}_{th}$ for heat. If coal for heat generation is directly substituted by the biomass fuel, the fossil comparator of $124 \text{ gCO}_{2eq}/\text{MJ}_{th}$ must be used.

$$Saving = \frac{EC_{F(el,h)} - EC_{B(el,h)}}{EC_{F(el,h)}}$$
[eq. 5]

Saving GHG emission savings of electricity and heat generation from biomass fuel compared to the fossil alternative

 $EC_{F(el,h)}$ Total emissions from electricity and heat generation from the fossil fuel comparator

 $EC_{B(el,h)}$ Total emissions from electricity and heat generation from biomass fuel

2.7 Biomass supply chain costs

The method for calculating the total costs of a feedstock supply chain involves all costs from the moment of cultivation or collection until conversion in the end-use facility, which is about analogous to the supply chain GHG emissions from eq. (1). In general, the supply chain costs can be calculated with eq. (6), adapted from Hoefnagels et al. (2014). The total supply chain costs of a biomass fuel can be compared to other biomass or fossil fuels with a similar end-use to evaluate the cost performance.

$$C = C_{ec} + C_p + C_{td} + C_{hq} + C_s + C_u$$
 [eq. 6]

С	Total biomass fuel production costs (e.g. in €/GJ)
C_{ec}	Costs of the extraction or cultivation of raw materials
C_p	Costs of processing (or pre-treatment)
C_{td}	Costs of transport and distribution
C_{hq}	Costs of handling and queuing
C_s	Costs of storage
C_u	Costs associated with conversion at the end-use facility

2.8 Levelised costs of energy

The levelised costs of energy (LCOE) is a commonly applied concept for determining the economic feasibility of a project, for instance in economic assessments of renewable electricity systems (Batidzirai et al., 2016). The LCOE is the cost price of the produced energy throughout the lifetime of the project (Blok & Nieuwlaar, 2017). The discounted investment, operation and maintenance and fuel costs over the project lifetime are divided by the total discounted energy output (eq. (7)). The terms capital expenditures (CAPEX) and operational expenditures (OPEX) are widely used terms in the LCOE concept to indicate respectively investment costs and operational and maintenance costs. These terms are used in the remainder of this report.

$$LCOE = \frac{\sum_{t=0}^{n} (I_t + OM_t + F_t) * (1+r)^{-t}}{\sum_{t=0}^{n} E_t * (1+r)^{-t}}$$
[eq. 7]

LCOE	Levelised costs of energy (e.g. €/MWh of generated electricity)
I_t	Investment in year t
OM_t	Operation and maintenance costs in year t
F _t	Fuel costs in year in year t
E_t	Energy output in year t
n	Lifetime or depreciation period of the installation
r	Discount rate

The LCOE allows for the comparison of a project to similar projects or a certain standard and herewith indicates the economic attractiveness of the project. In renewable electricity projects, for example,

the LCOE can be compared to a typical price (or cut-off price) for which generated electricity can be sold (Cervi et al., 2019b). In general, if the LCOE is higher than the value to which it is compared, the project is not cost-competitive and potentially not economically feasible. In such cases, it could thus be wiser to take no action at all or to consider an alternative project.

3 Method

The research method for assessing the GHG and cost performance of bagasse pellets from Peru is presented in this section. First, the case study of Peru and selected sugarcane mills are described. This is followed by the method of calculating GHG emissions and costs of the investigated supply chains. Then, the investigated supply chain is presented, followed by the method of calculations and data collection for determining the technical potential of bagasse and straw and the GHG emissions and costs of the bagasse pellet supply chain. Finally, the method for assessing the economic feasibility of local bioelectricity generation from straw as an alternative is described. An overview of data input for GHG and cost calculations is presented at the end of this section.

3.1 Case study

3.1.1 Sugarcane in Peru

Sugarcane is produced in many countries worldwide. Currently, Brazil is the largest producer with a production of 747 million tonnes in 2018 (FAO, 2020). Peru is number nineteen in global sugarcane production with a production of 10 million tonnes in 2018. On the other hand, sugarcane yields in Peru are one of the world's highest due to the favourable climate in the coastal area (Marcelo et al., 2017). In the period 2014-2018, the average sugarcane yield in Peru was 120.4 tonne/ha, compared to for instance 73.8 tonne/ha in Brazil (FAO, 2020). Land for sugarcane cultivation continues to be expanded by transforming desert areas to irrigated lands suitable for the growth of sugarcane (Nolte, 2019). Water for irrigation is obtained from nearby rivers or reservoirs. The favourable weather conditions allow for a year-round cultivation of sugarcane. Due to the year-round sugarcane cultivation, mills do not require to be very large since the harvest of sugarcane can be evenly spread throughout the year (Nolte, 2020). This is in contrast to for instance Brazil, where sugarcane harvesting and processing is seasonal (Hofsetz & Silva, 2012). Pre-harvest burning sugarcane fields is gradually being phased out in Peru, where it is already prohibited for sugarcane fields within a 1.5 km distance to populated areas (H. Davila – Coazucar⁴, personal communication, 3 July, 2020). Approximately 70% of the sugarcane fields in Peru is currently harvested mechanically and it is expected that mechanical harvest will be applied to all fields in the near future (C. Romero – MINAGRI⁵, personal communication, March 20, 2020).

Peru has fourteen sugarcane mills in the coastal area. Two relatively new sugarcane mills are mainly dedicated to ethanol production and the other sugarcane mills on sugar production (Nolte, 2019, 2020). Whereas all fourteen sugarcane mills use bagasse to generate steam in their boilers (Marcelo et al., 2017), ten sugarcane mills cogenerate electricity for processes in the sugarcane mill and only four generate surplus electricity to supply to the national grid (MINEM, 2018)⁶. The fourteen sugarcane mills are depicted in Figure 1 and additional information about the sugarcane mills is presented in Table 1. More detailed maps of the various regions with sugarcane mills are provided in Appendix A.

Selection of sugarcane mills

A selection is made of sugarcane mills that are included in the supply chain analysis. This selection is based on factors considering the expected GHG and cost performance of the bagasse pellets and on the practical potential for the setup of a bagasse pellet supply chain. First, the Chucarapi sugarcane mill is the only one that has an outlying location compared to the other sugarcane mills (Figure A1 in Appendix A) and has the lowest share in national sugarcane production (Table 1). It is expected that

 ⁴ Corporación Azucarera del Perú (Coazucar) is a holding company, owned by Grupo Gloria, which is composed of the Peruvian sugarcane mills AgroArurora, AgrOlmos, Casa Grande, Cartavio and San Jacinto (Coazucar, n.d.).
 ⁵ Ministerio de Agricultura y Riego (MINAGRI) is the Peruvian ministry of agriculture and irrigation.

⁶ Ministerio de Energía y Minas (MINEM) is the Peruvian ministery of energy and mining.

the costs per tonne pellet up to delivery at an export port are relatively high and the amount of delivered bagasse pellets is relatively low. Therefore, Chucurapi is excluded from this research.

Furthermore, whereas the Lambayeque region has the highest number of sugarcane mills, the contribution of these sugarcane mills to the national sugarcane production is among the lowest (except for AgrOlmos). AgrOlmos is located more in the north of Lambayeque (Figure A1 in Appendix A), whereas Pucalá, Tumán, Pomalca and Azucarera del Norte are clustered together in the south of Lambayeque. The latter four sugarcane mills are rather old with low-efficiency processes and outdated equipment compared to most other sugarcane mills in Peru (Bocci et al., 2009; López & Seclén, 2017). Similar to Chucurapi, costs up to delivery at the export port are expected to become rather high due to expected high costs for improving installations and processes in the sugarcane mill and for building a pellet plant with a relatively low pellet output. Moreover, there are socio-political concerns as news articles report on demonstrations, riots, unsafe work environments and corruption in these sugarcane mills (Canal N, 2018a, 2018b). Altogether, it is decided to exclude Pucalá, Tumán, Pomalca and Azucarera del Norte from the analysis. The nine remaining sugarcane mills are included in the investigated bagasse pellet supply chain.



Figure 1. Map of Peru with the sugarcane mills and export ports.

Orange triangles depict the sugarcane mills and yellow circles depict export ports. Yellow circles containing a black dot are export ports with a dry bulk terminal, required for handling bagasse pellets. The inventory of export ports is further explained in section 3.8.

Sugarcane mill	Region	Electricity for own use ¹	Electricity to national grid ¹	Sugarcane production in 2018 ² (ktonne)	Share of national sugarcane production ² (%)	Included in analysis
Caña Brava	Piura	Yes	Yes	1,182	9.7	Yes
AgroAurora	Piura	Yes	Yes	1,132	9.3	Yes
AgrOlmos	Lambayeque	Yes	No	1,034	8.5	Yes
Pucalá	Lambayeque	No	No	724	5.9	No
Tumán	Lambayeque	Yes	No	47	0.4	No
Pomalca	Lambayeque	No	No	785	6.4	No
Azucarera del Norte	Lambayeque	Yes	No	57	0.5	No
Casa Grande	La Libertad	Yes	No	2,011	16.5	Yes
Cartavio	La Libertad	Yes	No	1,289	10.6	Yes
Laredo	La Libertad	Yes	No	1,495	12.2	Yes
San Jacinto	Ancash	Yes	Yes	871	7.1	Yes
Paramonga	Lima	Yes	Yes	1,086	8.9	Yes
Andahuasi	Lima	No	No	724	5.9	Yes
Chucarapi	Arequipa	No	No	56	0.5	No

Table 1. Overview of sugarcane mills in the coastal area of Peru.

Sources: [1] MINEM (2018), [2] MINAGRI (2019).

3.1.2 Renewable energy auctions

The four sugarcane mills that supply surplus electricity to the national grid contribute to the slight share of 2% bioelectricity in the Peruvian electricity mix (MINEM, 2019). Subsidies for renewable energy projects for electricity generation in Peru are granted during national energy auctions (MINEM, 2017). Four of these auctions have occurred up until now in respectively the years 2009, 2011, 2013 and 2016 (Osinergmin, 2019). Only during the first auction in 2009, a subsidy was awarded to a bioelectricity facility fuelled by agricultural residues (i.e. bagasse): a 23 MW power plant of the sugarcane mill Paramonga with a granted subsidy of 52 US\$/MWh (44 €/MWh) (Clarke et al., 2018; Mitma, 2013). This value is used later on in this research for determining the economic feasibility of straw for local bioelectricity generation, which is further explained in section 3.3. Nonetheless, financial support through subsidies for bioelectricity projects remains rather low compared to the awarded subsidies to power generation facilities from other renewable energy sources. In the first three energy auctions, most subsidies were awarded to projects for hydroelectricity (Osinergmin, 2019), which already has a large share in the Peruvian electricity mix of 55.1% (MINEM, 2019). Subsidies awarded to solar and wind projects were only higher than hydro during the fourth energy auction. The awarded subsidies to bioelectricity projects were lowest during all four renewable energy auctions.

3.2 GHG performance

The GHG emissions of the bagasse pellet supply chain are assessed in a LCA from cradle-to-gate (up to electricity and heat generation from bagasse pellets). The methodology provided by the RED II is used to calculate the total supply chain emissions. Since the Dutch GHG target requires a minimum of 70% GHG savings for electricity and heat generation from biomass fuel in the Amer, it is assessed whether bagasse pellets from Peru comply with this target. Furthermore, an 80% GHG saving is required for installations starting operations from 2026 onwards, as set by the RED II. Whereas the use of bagasse pellets in an already operative facility is analysed, the potential of using bagasse pellets in other future end-use facilities in the Netherlands for electricity and heat generation is worthwhile to consider. Moreover, there is a possibility that the GHG target for existing installations in the Netherlands will become more stringent in the future to achieve climate goals. Therefore, the 80%

target is also taken into account in assessing the GHG performance of the bagasse pellets. The functional unit of biomass GHG emissions is set at 1 MJ pellets. The functional unit of GHG emissions for electricity and heat generation is set at respectively 1 MJ electricity and 1 MJ heat. The fossil comparators provided by the RED II are used to determine the GHG savings, which are 183 gCO_{2eq}/MJ_e for electricity and 124 gCO_{2eq}/MJ_{th} for heat generation (EC, 2018c). The latter is the specified comparator in case of direct substitution of coal with biomass.

Besides comparing the results to the fossil alternative, the supply chain GHG emissions are compared to the research of Derks (2018), who assessed the GHG performance of various white wood pellet types from the United States (U.S.) with end-use in the Amer. Only the GHG emissions of wood pellets made from sawmill residues (composed of mostly sawdust) are used as a comparison. This is because the pre-treatment process of wood pellets from sawdust consists of one drying step before fine grinding, conditioning and pelletising (Visser et al., 2020b), which is comparable to the requirements of converting bagasse to bagasse pellets (see section 3.8.2). The other white wood pellets assessed by Derks (2018) are produced from woody feedstocks that require more (energy-demanding) procedures during the pre-treatment stage, which would therefore not make a fair comparison for bagasse pellets. By comparing bagasse pellets with both wood pellets and the fossil alternative, conclusions are drawn on the GHG performance of the bagasse pellets.

3.3 Cost performance

The total costs of the bagasse pellet supply chain are calculated using eq. (6). All costs are converted to euro in the reference year 2018. Table A1 in Appendix B presents the used consumer price indexes (CPIs) and conversion rates to euros. A maximum cost limit is set on the bagasse pellet supply chain costs to avoid that the costs become too high. This is because the use of bagasse pellets is in competition with other biomass fuels (e.g. wood pellets), fossil energy (e.g. natural gas) or renewables (Visser et al., 2020a). In the research of Visser et al. (2020a), a maximum wood pellet cost based on price fluctuations in contract prices of industrial wood pellets from Canada and the U.S. was applied. A similar approach is applied in this research to set a maximum allowable cost range for the bagasse pellet costs. From 2015 to 2018, the industrial wood pellet prices fluctuated between 148 to $165 \notin$ /tonne pellet (FutureMetrics, 2018). These prices (converted to \notin/GJ using the lower heating value (LHV) of wood pellets) are used as respectively a lower and upper bound of maximum allowable bagasse pellet costs. This means that bagasse pellet supply at a cost within or below this range is acceptable, which is further referred to as the economic potential of bagasse pellets. Bagasse pellet costs exceeding the upper bound are considered not economically feasible.

Furthermore, the bagasse pellet costs are compared to reported costs in wood pellet supply chain studies to evaluate the cost performance. Beets (2017) studied the costs of white wood pellets from the U.S. with end-use in the Amer. These wood pellets are produced from mainly pine pulpwood to which several residuals are added. Producing wood pellets from pulpwood requires more size and moisture reduction steps during the pre-treatment stage compared to sawmill residues (Visser et al., 2020b), which logically results in higher pre-treatment costs for pulpwood. Moreover, raw feedstock costs of pulpwood are generally higher than sawmill residues. Comparing costs of bagasse pellets to wood pellets from pulpwood would therefore not make a fair comparison. However, since Beets (2017) considered the Amer as the end-use facility, it still useful to compare the wood pellets. As a second reference, the costs of wood pellets from sawdust as indicated by Visser et al. (2020b) are used as a more fair comparison for bagasse pellets.

As part of the cost assessment, the business case of local bioelectricity generation from straw at the sugarcane mill is assessed to determine its economic feasibility. This is done to assess the local bioenergy potential of straw and to determine whether it would be advisable for sugarcane mill

operators to invest in this option. The LCOE of local bioelectricity generation from straw is calculated for each sugarcane mill and compared to a typical bioelectricity cut-off price in Peru. The assumed bioelectricity cut-off price is based on the awarded subsidy for the bioelectricity plant, as indicated in section 3.1.2, which was $44 \in_{2009}$ /MWh or $52 \in_{2018}$ /MWh. Thus, a bioelectricity cut-off price of $52 \notin$ /MWh is assumed.

3.4 Sensitivity analysis

It is customary in GHG and cost analyses to assess the uncertainty of certain parameters in a sensitivity analysis. This way, it can be determined what the effect would be on the results if the value of a parameter ends up to be higher or lower than expected. It is especially useful to address uncertain parameters in stages that have a significant share in the total GHG emissions or costs. This is because a change in these stages could have a major effect on the outcomes and on whether certain thresholds or targets are met (e.g. GHG targets). Therefore, a sensitivity analysis is performed in this research, which is further presented in section 4.5, after presenting the results of the GHG and cost assessment.

3.5 Investigated supply chains

A bagasse pellet supply chain is investigated, from bagasse collection at the sugarcane mills in Peru up to the end-use of bagasse pellets in the Amer in the Netherlands. Figure 2a depicts the different stages of the investigated bagasse pellet supply chain in which the procedures of harvest and collection, pre-treatment, transport and end-use (as discussed in section 2.3) occur. The option of using straw in the boiler of the sugarcane mill for freeing up bagasse is considered in the bagasse pellet supply chain. In addition, the possibility of freeing up bagasse by implementing improvements in the sugarcane mill is included. Furthermore, the alternative use of straw for local bioelectricity generation is investigated, indicated by the straw supply chain (Figure 2b). The supply chains and data collection methods are explained in the following sections. First, the method of determining the technical potential of bagasse and straw is presented as the starting point for both supply chains.



(b) Straw supply chain



Figure 2. Bagasse pellet supply chain (a) and straw supply chain (b).

3.6 Bagasse and straw technical potential

The technical potential (or technical availability) of bagasse and straw is determined to identify the supply potential of these residues by the sugarcane mills. First, the theoretical potential is determined. The theoretical potential consists of the amount of bagasse and straw that could theoretically be obtained from sugarcane. One wet tonne of sugarcane stalks consists of 125 kg (dry) fibres, which is the main dry component of bagasse, and 140 kg (dry) straw (Seabra et al., 2010). The theoretical potential of bagasse and straw are determined based on sugarcane and bagasse production of the Peruvian sugarcane mills in the crop year 2018, as reported by MINAGRI (2019). Furthermore, the theoretical potential of straw also depends on whether the sugarcane fields are mechanically harvested. As explained before, this is currently the case for about 70% of the sugarcane fields and increasing to 100% in the near future. Hence, this research assumes two scenarios for the theoretical potential of straw, based on the mechanical harvest of respectively 70% (SC70) and 100% (SC100) of the sugarcane fields. Table 2 presents an overview and description of the assessed scenarios for determining the theoretical potential of straw.

The technical potential of straw consists of the amount of straw that can be collected from the field. As mentioned before, a share of produced straw should remain on the field for agro-ecological purposes. This sustainability criterium defines the sustainable technical potential (further referred to as 'sustainable potential') of straw, which thus consists of the theoretical potential deducted with the share that should remain on the field. There are many uncertainties about how much straw should remain on the field. This research assumes a value of 7.5 tonne straw per hectare that should remain on the fiend, in accordance with Hassuani et al. (2005) and Cervi et al. (2019a). The uncertainty of this value is further assessed in the sensitivity analysis.

The technical potential of bagasse is composed of multiple components, as indicated by the three components that compose the available bagasse in Figure 2a. Firstly, there is a potential of surplus bagasse, which is the share of produced bagasse currently not used in the sugarcane mill. Secondly, bagasse can be freed up by improving installations and processes at the sugarcane mill, which often requires investments for improved equipment. Thirdly, bagasse can be freed up by employing straw in the boiler of the sugarcane mill to replace a share of the used bagasse. This requires the collection of straw from the field and transport to the sugarcane mill, which comes together with additional GHG emissions and costs. In terms of costs, sugarcane mill operators would first sell surplus bagasse since this requires the least effort and is least costly. The next step would be to implement improvements at the sugarcane mill for freeing up bagasse. The final consideration is to collect straw for freeing up bagasse. Accordingly, three scenarios for the technical potential of bagasse for the bagasse pellet supply chain are assumed: 1) the collection of surplus bagasse at the sugarcane mill (SB), 2) the collection of both surplus bagasse and bagasse that is freed up by implementing improvements at the sugarcane mill (FBI) and 3) the collection of surplus bagasse, freed up bagasse from improvements at the sugarcane mill and freed up bagasse by using straw in the sugarcane mill boiler to replace bagasse (FBS). A description of the assessed scenarios for the bagasse pellet supply chain is presented in Table 2. The SB, FBI and FBS scenarios are assessed in the GHG and cost assessment of bagasse pellets.

Sugarcane mills that generate surplus electricity are assumed to have no surplus bagasse since all produced bagasse would likely go to the boiler. If sugarcane mills do not generate surplus electricity, a bagasse surplus of 33% from the total produced bagasse is assumed, based on Lopes et al. (2014). The amount of required straw for freeing up bagasse depends on the share of bagasse that could be substituted in the boiler. RWE has collaborated with the Brazilian energy company Raízen to assess the potentials for mobilising sugarcane residues at various Brazilian sugarcane mills (Esparza et al., 2020). Measures for freeing up bagasse, such as improving processes and equipment in the sugarcane mill and employing straw in the boiler, were taken into account in this pilot. It was found that, on average, 15% of the total bagasse used in the boiler can be freed up from substitution with straw and

an additional 5% of bagasse can be freed up by implementing miscellaneous process improvements at the sugarcane mill (M. Bouwmeester – RWE, personal communication, 12 February, 2020). These values are assumed in this research for freeing up bagasse. Based on the LHV of bagasse and straw, the required amount of straw to substitute bagasse is calculated. Note that since only 15% of bagasse used in the boiler is assumed to be replaced by straw, the required volumes of straw would be far below the sustainable potential. The remaining sustainably available straw on the field after deducting the share used for freeing up bagasse could be used for other purposes. These other purposes are, however, not further addressed within the scope of the bagasse pellet supply chain.

Scenario	Description	Specification				
Bagasse pell	Bagasse pellet supply chain					
SB	Collection of surplus bagasse at the sugarcane mill	33% of total bagasse production				
FBI	Collection of both surplus bagasse and bagasse that is freed up by implementing improvements at the sugarcane mill	33% of total bagasse production and 5% of bagasse supplied to the boiler of the sugarcane mill				
FBS	Collection of surplus bagasse, freed up bagasse from improvements at the sugarcane mill and freed up bagasse by using straw in the sugarcane mill boiler to substitute bagasse	33% of total bagasse production, 5% + 15% of bagasse supplied to the boiler of the sugarcane mill				
Straw supply chain						
SC70	70% of the sugarcane fields are mechanically harvested	Straw production on 70% of harvested sugarcane areas				
SC100	100% of the sugarcane fields are mechanically harvested	Straw production on 100% of harvested sugarcane areas				

Table 2. Description of assessed scenarios for bagasse and straw potentials.

3.7 Straw supply chain

Although the straw supply chain for local bioelectricity (Figure 2b) is not the main focus of this research, the applied method and data input for this supply chain are partly used in the bagasse pellet supply chain as well. For reasons concerning the structure of the report, the applied method for addressing the straw supply chain is presented first.

3.7.1 Collection and transport to the sugarcane mill

The sustainable potential of straw can be collected from the field and transported to the sugarcane mill. Straw can be recovered through different routes. Michelazzo (2005) found that the baling recovery route, which entails windrowing and baling of straw on the field, is a promising option due to a high energetic quality of straw delivered at the sugarcane mill. It is therefore assumed that straw is collected through the baling method. Straw bales are subsequently assumed to be transported to the sugarcane mill via trucks.

The transport distance from the fields to the sugarcane mills is determined in a spatially explicit approach using ArcGIS⁷. Figure 3 depicts various procedures of the spatial analysis in ArcGIS for the sugarcane mill AgroAurora. First, a layer containing the sugarcane mill locations is created (Figure 3a). Then, the sugarcane fields surrounding each sugarcane mill are mapped by manually creating polygons surrounding the sugarcane areas (Figure 3b). The sugarcane fields are identified using Google Streetview and by following the pattern of the sugarcane fields from top view when creating the polygons. The mapped sugarcane fields in ArcGIS are verified as much as possible with available maps from sugarcane mill operators and through personal communication with sugarcane mill operators.

⁷ ArcGIS version 10.8.1 is used for the spatial analyses in this research.

Moreover, the mapped hectares of sugarcane fields are verified with the cultivated hectares of sugarcane fields as reported by MINAGRI (2019).



Figure 3. Spatial analysis of Peruvian sugarcane fields in ArcGIS.

(a) Sugarcane mills (indicated by the orange triangle) are identified, (b) sugarcane fields are mapped in polygons, (c) a fishnet is created to split the polygons into small squares.

Next, two tools of ArcGIS are used to find the average transport distance from the sugarcane fields to the nearby sugarcane mill. The near tool measures the direct distance of a polygon to the sugarcane mill. However, this only measures the shortest distance of the outer polygon to the sugarcane mill. Therefore, the fishnet tool is used to split the polygons into small squares (Figure 3c). The direct distance from each square to the sugarcane mill is subsequently measured with the near tool. The average of these distances is calculated, which represents the average transport distance from the sugarcane mill. Finally, a tortuosity factor of 1.4 is applied to correct for the tortuosity of unpaved roads (Cervi et al., 2019b). These procedures are executed for all nine sugarcane mills.

The straw collection costs (or farmgate costs) and transport costs are composed of among others machinery, labour and fuel. Additionally, farmgate costs include costs of required agricultural input to compensate for nutrient losses from removing a share of straw from the field. Cost input for straw farmgate and transport costs is retrieved from Cervi et al. (2019b).

3.7.2 Local bioelectricity generation

For local bioelectricity generation at the sugarcane mill from straw, it is assumed that all sustainably available straw is used to generate surplus electricity, which is supplied to the national grid. As described before, sugarcane mill operators possibly have to improve existing installations and have to invest in, among others, larger boilers and a connection to the national grid. Due to a lack of data on the status of the existing installations in the sugarcane mills and on (country-)specific investments in e.g. larger boilers, it is decided to use the techno-economic parameters applied by Cervi et al. (2019b) to calculate the LCOE. Cervi et al. (2019b) provide the required investments in Brazil for an assumed new power plant adjacent to the sugarcane mill, which is entirely dedicated to generating bioelectricity from straw. The cost parameters are presented in Table A6 in Appendix C. Note that in reality, however, it would be more cost-effective to use and improve the existing installations in the sugarcane mill to the best possible extent rather than invest in a new power plant. The uncertainty in required investments is addressed in the sensitivity analysis.

The annual CAPEX, OPEX and straw costs are determined for each sugarcane mill to calculate the LCOE. It is assumed that sugarcane mills already connected to the national grid do not have to invest in a grid connection and transmission lines. For the sugarcane mills that are not yet connected, the direct distance from the sugarcane mill to the nearest electrical substation is measured with ArcGIS to calculate the transmission line costs. A map of the Peruvian electricity network, retrieved from MINEM (n.d.), is used to identify the nearest substation locations.

The required scale of the power plant is determined by the annual feedstock supply. It is assumed that the boiler in the new plant is supplied with both straw and bagasse to overcome the technical limitations of only combusting straw (Cervi et al., 2019b). The boiler is assumed to be supplied with all sustainably available straw and the volumes of surplus bagasse from the sugarcane mill, which amounts to the beforementioned 33% of total produced bagasse. Bagasse is assumed to be available at zero costs for the sugarcane mill operator since this is a residue at the sugarcane mill. The LHV of bagasse and straw and the electric conversion efficiency are used to calculate the annual electric output of the power plant. Based on the range in the electrical conversion efficiency of 20-35% in Brazilian biomass CHP plants (Cervi et al., 2019a), an electrical conversion efficiency of 25% is assumed. Finally, the LCOE is compared to the bioelectricity cut-off price of 52 €/MWh to determine the economic feasibility of using straw for local bioelectricity generation.

3.8 Bagasse pellet supply chain

The stages of the bagasse pellet supply chain are described next in the following order: collection, pretreatment, transport (domestic and international shipping) and end-use.

3.8.1 Collection

The available bagasse can be collected at the sugarcane mill. The assumed costs of surplus bagasse are based on the price that sugarcane mill operator could obtain for the alternative use of surplus bagasse, such as the price for supplying bagasse-generated electricity to the national grid. Currently, sugarcane mill operators can supply surplus electricity to the national grid for $25 \notin$ /MWh or directly to clients for $37 \notin$ /MWh (D. Tsuchida – Caña Brava, personal communication, 15 May, 2020). The price of selling electricity to clients, i.e. $37 \notin$ /MWh, is used to determine the costs of surplus bagasse. Taking into account that a traditional sugarcane mill generates 125 kWh per tonne steam and 2 tonne steam per tonne bagasse (Lopes et al., 2014; Nolte, 2020), the assumed costs of surplus bagasse amount to $9.3 \notin$ /tonne raw bagasse.

Costs for freeing up bagasse are composed of two components: investments for equipment and process improvements in the sugarcane mill and costs for employing straw in the boiler of the sugarcane mill to substitute bagasse. Literature is consulted to determine typical investment costs for equipment and process improvements in the sugarcane mill. Considered improvements include increased pressure and temperature in Rankine cycles, improved thermal recovery through larger use of steam evaporation, electrification of drives by steam turbines, improved equipment and optimised process management (e.g. Bocci et al., 2009; Dos Santos & Ramos, 2020). The values found in literature are compared and verified with the estimated costs for freeing up bagasse in the pilot of RWE and Raízen. A range of 10-21 \notin /tonne bagasse for implementing improvements is found in literature. The costs of freed up bagasse from improvements at the sugarcane mill are therefore assumed to be 15.5 \notin /tonne bagasse. The costs for freeing up bagasse by using straw in the boiler is assumed to be composed of costs for straw collection from the sugarcane field and transport costs to the sugarcane mill. The method presented in section 3.7 is applied to determine the straw collection and transport costs.

3.8.2 Pre-treatment

It is assumed that bagasse has to undergo pre-treatment since the supply chain involves a longdistance transport stage (i.e. international shipping), for which a pre-treatment stage is recommended (see section 2.3). Bagasse is therefore assumed to be transported from the sugarcane mill to a pellet plant. Bagasse pellet plants do not yet exist in Peru (G. Nolte – United States Department of Agriculture (USDA), personal communication, 20 February, 2020). Therefore, optimal pellet plant locations are selected based on conditions regarding bagasse availability and transport distances. A first condition is that a pellet plant should be located in the proximity to several surrounding sugarcane mills, wherever possible. This is done to maximise feedstock supply to the pellet plant from multiple sugarcane mills and to minimise the transport distance of raw feedstock to the pellet plant. A second condition is that pellet plants should be positioned on strategic locations regarding the transport routes from the sugarcane mill to the export terminal. It is assumed that trucks are used for transport from the sugarcane mill to the pellet plant and from the pellet plant to the export terminal, which is further explained in section 3.8.3. If the on-land transport routes from sugarcane mills to the export terminal intersect, this intersection is chosen as a potential pellet plant location. Besides considering these two conditions for determining appropriate pellet plant locations, an alternative approach was considered. This approach involves locating the pellet plants at the export port. The reason for considering this approach is because the sugarcane mills are already located relatively near to the export port, since both are located in coastal area. Transporting raw bagasse directly to the export terminal could reduce the required handling and storage steps in the supply chain. This potentially decreases the supply chain costs up to delivery at the export terminal. However, larger transport distances with raw biomass generate higher GHG emissions and costs per unit of energy during the transport stage.

Therefore, an intermediate analysis is performed in which the two options of locating pellet plants at route intersections or at the export terminal are considered. All transport GHG emissions and costs up to delivery at the export terminal are calculated to determine the best option in terms of GHG and cost performance. The optional pellet plant locations are spatial explicitly mapped with ArcGIS. First, the sugarcane mills and potential export port locations are mapped. Only export ports with a dry bulk terminal are included (explained in section 3.8.3). Then, a publicly available road network layer, retrieved from OpenStreetMap (n.d.), of roads in Peru is added. The road network analysis tool is used to determine the shortest routes from the sugarcane mills to the nearest export terminal and to measure the transport distances of these routes. The pellet plants are subsequently located at the intersection of routes as depicted in Figure 4. The other optional pellet plant locations are selected at the export terminals.



Figure 4. Road network analysis in ArcGIS to determine optimal pellet plant locations. The numbers 1, 2 and 3 depict respectively sugarcane mills (Caña Brava above and AgroAurora below), the potential pellet plant located at the intersecting routes and the nearest export terminal.

It is found that locating the pellet plants at route intersections resulted in lower supply chain GHG emissions and costs up to pellet supply at the export terminal. In addition, an alternative option of locating individual pellet plants next to the sugarcane mills AgrOlmos and San Jacinto is considered. This is done because the transport distance from these sugarcane mills to their nearest export terminals or to the location of intersecting routes is relatively long, which would lead to high transport GHG emissions and costs. It is found that locating individual pellet plants next to AgrOlmos and San Jacinto resulted in lower GHG emissions and costs up to delivery at the export terminal, compared to the other two options. In summary, pellet plants are assumed to be located at the intersection of

routes from the sugarcane mills to the export port, whereas AgrOlmos and San Jacinto specifically are assumed to have an individual pellet plant next to the sugarcane mill. The produced pellets from the latter two sugarcane mills would subsequently be transported to the export terminal following the shortest route.

The pre-treatment process of bagasse is similar to wood pellets from sawmill residues, with the following operations: drying, grinding, conditioning, pelleting and cooling (De Almeida et al., 2017; Vera et al., 2019). Heat for the drying process is preferably provided by combusting a low-grade biomass feedstock as support fuel, such as sugarcane straw (M. Bouwmeester – RWE, personal communication, 1 July, 2020). As described before, the combustion of straw in boilers, originally dedicated to bagasse combustion, has technical limitations. However, boilers dedicated to straw combustion are currently being developed and applied for small-scale purposes, such as for heating homes (Kristensen et al., 2017; Kubica et al., 2016). Given the fact that pellet plants still have to be built in Peru, it would thus be technically possible to invest in a boiler dedicated to straw combustion. Therefore, it is assumed that straw is used as support fuel for the pre-treatment process. Straw is assumed to be collected from the surrounding sugarcane mills and transported to the pellet plant. The required straw is calculated with the required heat for bagasse as reported by Vera et al. (2019) are used for these calculations. Furthermore, it is assumed that required electricity is supplied by the national grid.

Since the pre-treatment process of bagasse pellets is similar to wood pellets, the required installations for a bagasse pellet plant are similar to those of wood pellets. Hence, the costs of bagasse pretreatment in this research are based on pre-treatment costs reported in wood pellet studies. Visser et al. (2020b) conducted a literature review of wood pellet studies and provided an inventory of the supply chain costs, including the costs of the pre-treatment stage for pellet plants of ranging scales. The CAPEX and OPEX presented by Visser et al. (2020b) are used and converted to a reference capacity of 100,000 tonne pellets per year to find the average pellet costs at this scale. Scale factors for capital and labour are applied to calculate the pre-treatment costs for the bagasse pellet plants. Literature is consulted to find typical values of energy consumption in the pre-treatment stage. The measured transport distances of straw (explained in section 3.8.3) and farmgate and transport costs of straw presented in section 3.7 are used for calculating GHG emissions and costs of using straw as support fuel.

3.8.3 Transport

The used transport modes for the transport stages are chosen based on the type and amount of transported feedstock, transport distances and the existing transport network. As is common for the transport of raw feedstock, it is assumed that trucks are used for bagasse transport to the pellet plant and straw transport to the sugarcane mill and the pellet plant. It is assumed that straw is transported over the measured average distance from the sugarcane field to the sugarcane mill (section 3.7.1) and a share is subsequently transported to a pellet plant as support fuel. This means that a share of straw from the entire stretch of the sugarcane fields is assumed to be collected. Note that in reality, however, the sugarcane mill and pellet plant would logically be supplied with all sustainably available straw from the most nearby sugarcane fields to minimise the transport distance.

For determining the appropriate transport mode for transporting pellets from the pellet plants to potential export ports, it is investigated whether a sufficient railway network is present. Although few export ports are connected to a railway terminal, the railway network is mainly located land inwards in central and southeast Peru (MTC, 2019), whereas the sugarcane mills are rather located on the coast in central and northwest Peru. Therefore, the railway mode is found insufficient for bagasse pellet transport to the export ports. Since the transport distances from sugarcane mills to export ports

are relatively low due to their locations in coastal area, it is assumed that trucks are used for bagasse pellet transport to the export port. Next, export ports containing a terminal suited for bagasse pellet handling and shipping are selected to determine the nearest export port for each sugarcane mill. Peru has seven major export ports with four of them located in the regions of the investigated sugarcane mills (Figure 1): Paita (Piura), Salaverry (La Libertad), Chimbote (Ancash) and Callao (Lima) (Urrunaga & Aparicio, 2008). The port of Chimbote does not have a dry bulk terminal (Autoridad Portuaria Nacional, 2018), required for handling bagasse pellets, and is therefore excluded from the analysis.

The transport distances from the sugarcane mill to the pellet plant and from the pellet plant to the export terminal are calculated with the road network analysis of ArcGIS (Figure 4), as explained in section 3.8.2. The transport distance of straw to the pellet plant is assumed to be the sum of the transport distance from sugarcane field to sugarcane mill (section 3.7) and sugarcane mill to the pellet plant. The costs of truck transport consist of fixed costs for e.g. loading and unloading and variable costs for e.g. fuel, repair and maintenance, labour and capital (Hoefnagels et al., 2014). Country-specific cost factors of truck transport are retrieved from local data sources. The transport time is multiplied with a factor 2.5 as applied by Visser et al. (2020b) to account for empty returns, breaks and delays. The diesel consumption of trucks is calculated to determine the GHG emissions and costs of diesel use.

At the export terminal, bagasse pellets are unloaded and potentially stored before international shipping to the import terminal of Rotterdam in the Netherlands. The type of appropriate deep-sea vessel is first determined based on vessel size restrictions at the export and import terminal and during the shipping route. It is found that only Handysize vessels can access the ports of Paita and Salaverry due to port size restrictions, whereas the port of Callao allows the access of Supramax vessels (Serpac, n.d.). It is therefore assumed that Handysize vessels are used for bagasse pellets transported from the ports of Paita and Salaverry. The appropriate vessel (i.e. Handysize or Supramax) for export from the port of Callao is determined based on the potential annual supply of bagasse pellets to this port. It is assumed that a minimum of three shipments per year from this port should occur since costs and space requirements for long-term storage of bagasse pellets could lead to higher supply chain costs. Therefore, at least one compartment of the vessel should be fully loaded with bagasse pellets three times a year. If, for instance, the annual pellet production is too low, a Supramax vessel compartment could not be fully loaded three times a year. It is then assumed that a Handysize vessel is used since this could economically be the better option. The ocean transport distances are found using a tool for sea route and distance calculations (SeaRoutes, n.d.). The fuel consumption of deep-sea vessels is calculated with the method applied by Visser et al. (2020b). The costs for handling and storage at the export terminal and the time charter rates (e.g. depreciations, maintenance, repairs, insurance of machinery, supply crew) for deep-sea shipping are retrieved from literature. The average price of heavy fuel oil (HFO) in Peru is used to calculate the fuel costs.

At the import terminal of Rotterdam in the Netherlands, bagasse pellets are transloaded to barge ships and transported over 50 km to the Amer in Geertruidenberg (Derks, 2018). Literature is consulted to determine the barge ship fuel consumption and costs.

3.8.4 End-use

Pellets delivered to the Amer are pneumatically unloaded, stored, deagglomerated (or pulverised) and combusted in the boiler together with coal (M. Bouwmeester – RWE, personal communication, March 27, 2020). The current co-firing rates at the Amer are 80% biomass and 20% coal. The processes before final pellet combustion require electricity. The required electricity consumption and costs for processes in the end-use stage are retrieved from literature.

Processing biomass in the mills of the Amer leads to losses in efficiency losses compared to coal due to multiple reasons (E. van Dorp – RWE, personal communication, 21 September, 2020). Firstly, fuels are ground and dried in the mills with incoming outside air which is preheated with hot air from boiler flue gases. Bagasse pellets require a lower air temperature (140-160 °C) compared to coal (240-300 °C). Since incoming air is less heated and flue gases are less cooled, the relatively high temperature of flue gases leaving the system results in efficiency losses. Secondly, due to the lower LHV of biomass pellets compared to coal, more input of biomass fuel is required for the same energy output. This generates more flue gases which require more air circulation, for which more energy input is required. Thirdly, the grinding of biomass in the mill produces larger particles than the grinding of coal. Moving these larger particles also requires more air circulation. These efficiency losses are taken into account for calculating the efficiency of electricity and heat generation from bagasse pellets at the Amer.

3.9 Data inventory

This section provides the data input for the GHG and cost calculations in addition to the beforementioned assumed values. Additional data input is provided for the collection, pre-treatment, transport and end-use stage. Furthermore, Appendix C provides general data input regarding among others emissions factors, LHVs, general costs and assumed weight losses in the supply chain. Also, specified data input for each sugarcane mill regarding measured transport distances and production values of sugarcane, bagasse and straw is presented in Appendix D.

Table 3 presents input data on feedstock characteristics and straw collection and transport. Straw is composed of green tops, green leaves and brown leaves that have a different MC of respectively 82.3, 67.7 and 13.5% (Leal et al., 2013). It is assumed that straw is generally available at a MC of 15%, in accordance with Seabra et al. (2010) and Cervi et al. (2019a). When straw remains on the field for a drying period of 10-15 days after sugarcane harvest, this MC can be reached naturally (Cervi et al., 2019a).

	Unit		Value	
Feedstock characteristics	Bagasse	Straw		
Dry content per wet tonne sugarcane stalks	tonne dry/tonne wet sugarcane stalks	12.5	14.0	1
Moisture content	wt%	50	15	1
Straw collection and transport				
Amount remaining on field	tonne dry/ha	7.5		2
Diesel consumption	L/ha	52.2		3
Farmgate costs	€/tonne dry	16.63		4
Straw transport costs	€/(tonne*km)	0.17		5, 6

Table 3. Input data on bagasse and straw characteristics, straw collection and straw transport.

Sources: [1] Seabra et al., 2010, [2] Carvalho et al. (2017), [3] Cardoso et al. (2013), [4] Cardoso et al. (2015), [5] Cervi et al. (2019b), [6] Michelazzo (2005).

Data input for the pre-treatment stage is provided in Table 4. The calculated costs for a 100,00 tonne/y plant, as explained in section 3.8.2, are presented. Costs in the category 'other' include among others insurance rates, taxes and administration costs (Thek & Obernberger, 2004). Consumables include costs of office tools, lubricants, die and rollers (Pirraglia et al., 2013). The average hourly wage used in the wood pellet studies reviewed by Visser et al. (2020b) was based on wages in e.g. the U.S., Sweden and Austria. The calculated labour costs for the reference plant are indicated with 'high wage' between brackets. However, the average hourly wage in Peru of $4.38 \notin/h$ (Table A4 in Appendix C) is significantly lower. Therefore, labour costs in \notin /tonne pellet are divided by the 'high wage' and multiplied with the Peruvian wage to find a more representable value for Peruvian labour costs per tonne pellet produced. This is indicated in Table 4 by 'Labour (Peru wage)'. Note that the other cost

parameters are not assumed to be lower for Peru since pellet equipment is produced and traded globally (Visser et al., 2020b). These cost parameters are therefore not assumed to be country-specific.

	Unit	Value	Source
Boiler efficiency	%	85	1
Electricity consumption	kWh/tonne pellet	90.3	1
Heat requirement	kJ _{th} /MJ pellet	207	1
Diesel consumption	kJ/MJ pellet	1.6	2
Scale factor capital	-	0.85	3
Scale factor labour	-	0.25	3
Average hourly wage	€/h	20	3
Costs for a 100,000 tonne/y plant			
Capital expenditures	€/tonne pellet	9.17	3
Maintenance	€/tonne pellet	2.70	3
Other	€/tonne pellet	7.89	3
Consumables (other than	€/tonne pellet	13.71	3
biomass or energy)			
Labour (high wage)	€/tonne pellet	13.77	3
Labour (Peru wage)	€/tonne pellet	2.63	-

Table 4. Input data for bagasse pre-treatment.

Sources: [1] Vera et al. (2019), [2] Giuntoli et al. (2017), [3] Visser et al. (2020b).

Table 5 presents input data for the transport modes truck, deep-sea vessel and barge vessel. The fuel consumption of trucks and barge ships includes fuel use for empty trips, which account for 50% of total trips. A complete overview of data input for deep-sea shipping is presented in Table A7 in Appendix C. The pellet load per compartment is calculated assuming that Handysize and Supramax vessels have five separate load compartments (OpenSea, n.d.).

Finally, data input for the end-use stage at the Amer is presented in Table 6. The electrical and thermal efficiency are used for calculating the GHG emissions of electricity and heat generation from bagasse pellets. The Carnot efficiency is based on the value that can be assumed when useful heat is generated below 150°C, as stated by the RED II, which is in accordance with the assumptions made by Derks (2018) for electricity and heat generation at the Amer.

Table 5. Input data for transport stages.

	Unit	Value		Source		
Truck transport						
Bagasse load per truck	tonne/truck	25		1		
Straw bales load per truck	tonne/truck	26.5		2		
Maximum speed	km/h	80		3		
Loading and unloading time	h	1		1		
Diesel use loading and unloading	L	6.4		4		
Diesel use road	L/(truck*km)	0.61		5		
Variable costs: repair, maintenance, road tolls	€/km	0.18		6		
Variable costs: capital, equipment, administration	€/h	2.16		6		
Handling at export and import terminal						
Diesel use handling	L/tonne pellet	0.048		7		
Electricity consumption handling	kWh/tonne pellet	0.791		7		
Export terminal costs	€/tonne pellet	4.6		8		
Import terminal costs	€/tonne pellet	5.6		9		
Deep-sea shipping		Handysize	Supramax			
Maximum pellet load	tonne	22,533	46,800	1		
Maximum pellet load per compartment	tonne	5,200	10,800	-		
HFO consumption	g/(tonne*km)	2.5	1.6	1		
Charter rate	€/h	479	667	10		
Barge shipping						
Maximum load	tonne/vessel	2,842		11		
Marine diesel oil (MDO) consumption	MJ/(vessel*km)	915		1		
Barge shipping costs	€/(tonne*km)	0.052		9		

Sources: [1] Visser et al. (2020b), [2] Cardoso et al. (2013), [3] OISEVI (n.d.), [4] Lindholm et al. (2010), [5] Smeets et al. (2009), [6] MINCETUR (2015), [7] Derks (2018), [8] MINCETUR (n.d.), [9] Sikkema et al. (2010), [10] Hoefnagels et al. (2014), [11] Roelse (2002).

Table 6. Input data for the end-use stage.

	Unit	Value	Source
Electricity consumption for pulverising pellets	kWh/tonne pellet	50	1
End-use costs	€/tonne pellet	0.9	2
Electrical efficiency at 100% coal firing	%	41.8	3
Thermal efficiency at 100% coal firing	%	3.7	3
Efficiency loss bagasse pellets at 80% biomass pellet co-firing	Percentage point	0.8	4
Carnot efficiency	-	0.3546	5

Sources: [1] Agar (2017), [2] Derks (2018), [3] Sikkema et al. (2010), [4] E. van Drop – RWE, personal communication, 21 September, 2020, [5] EC (2018c).

4 Results

This section presents the results of the GHG and cost assessment of the bagasse pellet supply chain. First, the technical potential of bagasse supply in the SB, FBI and FBS scenarios is presented. This is followed by the outcomes of the GHG emission and cost calculations. Then, the results of the LCOE of straw for local bioelectricity generation are presented. Finally, the sensitivity analysis of the GHG and cost performance and the LCOE is provided, including an explanation of the varied parameters and the outcomes of the sensitivity analysis.

4.1 Bagasse technical potential

The technical potential of raw bagasse that could be supplied by the sugarcane mills is calculated for the scenarios SB, FBI and FBS. Figure 5 depicts the technical bagasse potential in ktonne per year per region where bagasse pellets are potentially exported from (i.e. Piura, La Libertad and Lima). The technical supply potential of bagasse pellets delivered to the Amer is depicted in Figure 9 in section 4.3, where it is further discussed. The highest bagasse potential for all scenarios is from the region La Libertad, followed by Piura and finally Lima.





A breakdown is provided of surplus bagasse, freed up bagasse by implementing improvements at the sugarcane mill and freed up bagasse by using straw to replace a share of used bagasse in the boiler of the sugarcane mill. Values above data columns represent the total technical potential.

4.2 GHG performance

The GHG emissions for each stage of the supply chain are calculated for the SB, FBI and FBS scenarios. Figure 6 depicts the GHG emissions per MJ pellet for each region. The major contributing stages to the GHG emissions are pre-treatment, deep-sea shipping and end-use. Straw collection also has a significant contribution in the FBS scenario. There is a slight difference in total GHG emissions between the SB and FBI scenarios related to the bagasse transport stages from sugarcane mill to pellet plant and from pellet plant to export terminal. Since installations and process improvements in all sugarcane mills are assumed in FBI, bagasse is available at all sugarcane mills and has to be transported to the pellet plant. This is in contrast to SB, where it is assumed that only bagasse is collected from sugarcane mills that have surplus bagasse. However, the difference in total GHG emissions between SB and FBI are negligibly small.

In the SB and FBI scenarios, bagasse pellets from La Libertad have the lowest GHG emissions per MJ pellet. This can be ascribed to relatively low transport GHG emissions from pellet plant to the export terminal due to low transport distances. In FBS, however, bagasse pellets from Lima have the lowest GHG emissions per MJ pellet due to the lower GHG emissions for deep-sea shipping. It is assumed that a Supramax vessel is used for shipping bagasse pellets from Lima in FBS, whereas the Handysize is used for Piura and La Libertad. In FBS, the potential bagasse pellet supply of Lima is high enough to enable at least three shipments with the Supramax vessel, which is not the case in SB and FBI. The lower fuel consumption per tonne*km of the Supramax leads to the significantly lower shipping GHG emissions. If a Handysize vessel would be preferred in practice (e.g. due to not fully loaded return trips), bagasse pellets from La Libertad would have the lowest GHG emissions in all scenarios.



Figure 6. GHG emissions per MJ pellet per region for the SB, FBI and FBS scenarios.

A breakdown of GHG emissions per stage of the bagasse pellet supply chain is depicted. Values above data columns represent the total GHG emissions.

The GHG emission savings for electricity and heat generation from bagasse pellets are depicted in Figure 7. Only the results of SB and FBS are presented since the FBI scenario resembles the results of the SB scenario. The results from the research of Derks (2018) for white wood pellets are also depicted in this figure. The bagasse pellets from all regions and in all scenarios comply with the Dutch GHG target of 70% GHG savings. Therefore, bagasse pellets sourced from Peru and produced from surplus bagasse, freed up bagasse from improvements and freed up bagasse from substitution by straw can be used as biomass fuel in existing power plants in the Netherlands. Furthermore, the bagasse pellets have potential to comply with an 80% GHG saving target, but this could become more challenging (especially for the FBS scenario). When comparing the GHG performance of bagasse pellets to wood



pellets, it can be observed that bagasse pellets have potential to outperform wood pellets in the SB scenario. The GHG emissions in FBS are mostly comparable to the wood pellets.

Figure 7. GHG emission savings of electricity and heat generation from bagasse pellets.

The results of Derks (2018) on GHG emission savings of white wood pellets are depicted on the right. Values above data columns represent the total GHG emission savings.

4.3 Cost performance

The costs of the bagasse pellet supply chain in SB, FBI and FBS are depicted in Figure 8. The major contributing stages to the total costs are surplus bagasse collection, straw collection for freeing up bagasse (FBS), pre-treatment and deep-sea shipping. The total pellet costs in FBI are slightly higher than SB for Piura and La Libertad and equal for Lima. Whereas costs per tonne pellet in FBI increase due to investments for equipment and process improvements at the sugarcane mill, the costs per tonne pellet decrease in the pre-treatment stage due to economies of scale. Therefore, the total bagasse pellet costs in FBI are only slightly higher or remain equal to the total costs in SB. Total bagasse pellet costs increase significantly in FBS for especially Piura and La Libertad, which can mainly be ascribed to the costs for straw collection.

Bagasse pellets from La Libertad perform best in terms of costs in all three scenarios. La Libertad greatly benefits from economies of scale due to the relatively high technical potential of bagasse (Figure 5). This can be observed in for instance pre-treatment costs and costs of improving installations and processes at the sugarcane mill. Implementing improvements in larger sugarcane mills (with high bagasse production and use in the boiler) will free up more volumes of bagasse than small sugarcane mills. This leads to relatively low costs per tonne bagasse in this stage. Furthermore, the short transport distances to the export terminal for La Libertad lead to low transport costs in this stage.



Figure 8. Results of bagasse pellet costs in €/tonne pellet.

A breakdown of costs per stage of the bagasse pellet supply chain is depicted. Values above data columns are the total supply chain costs.

Figure 9 depicts the cost-supply curve per region for the potential bagasse pellet supply up to supply at the Amer. The curves show the potential pellet supply in the subsequent scenarios SB, FBI and FBS and the respective average bagasse pellet costs in these scenarios. Additionally, the maximum allowable supply chain costs of 8.5-9.4 €/GJ, based on industrial wood pellet prices, is depicted in Figure 9 by the lower and upper bound cost limits. It can be observed that La Libertad has the highest supply potential, followed by Piura and finally Lima. The average bagasse pellet costs remain below the upper bound of 9.4 €/GJ. The bagasse pellets are therefore considered to be economically feasible and competitive with wood pellets. The pellet costs remain below the lower bound of 8.5 €/GJ when supply in the SB and FBI scenarios are considered. The economic potential of bagasse pellet supply below the lower cost limit is 6 PJ/y (or 402 ktonne pellets/y). The average pellet costs in the FBS scenario are within the allowable cost range, representing an additional economic potential of 2.9 PJ/y(or 196 ktonne pellets/y). It can be stated that bagasse pellets produced from surplus bagasse and freed up bagasse by improvements at the sugarcane mill show much potential to be competitive with wood pellets. The average costs of bagasse pellets in FBS are significantly higher, which confines the competitiveness of these bagasse pellets. It should therefore be considered whether it is worthwhile to collect and transport straw for freeing up bagasse, especially for the regions Piura and Lima where the additional supply potential is relatively low compared to La Libertad.



Figure 9. Cost-supply curve of bagasse pellet supply up to the Amer.

The bagasse pellet costs per GJ pellet are depicted in Figure 10, together with the total pellet costs of white wood pellets from Beets (2017) and Visser et al. (2020b) for comparison. It can be observed that bagasse pellets of each region in SB and FBI are lower than the results from Beets (2017). In FBS, the bagasse pellet costs are about equal to wood pellets from Beets (2017). When comparing bagasse pellets with wood pellets from Visser et al. (2020b), it can be observed that especially the bagasse pellets from La Libertad in SB and FBI have potential outcompete wood pellets. In the FBS scenario, however, the bagasse pellets from all three regions perform worse than wood pellets in terms of costs.





The results of Beets (2017) and Visser et al. (2020b) on total costs of white wood pellets, expressed in ξ_{2018} , are depicted on the right. Values above data columns represent the total supply chain costs.

4.4 Straw for local bioelectricity

To determine the economic feasibility of using straw for local bioelectricity, the LCOE is calculated for each sugarcane mill for the scenarios SC70 and SC100. The results of these calculations are depicted in Figure 11. The major contributing stages to the total costs are the CAPEX (fixed capital investment (FCI) and working capital) and OPEX. Andahuasi has a significantly higher LCOE compared to the other sugarcane mills. Due to a low electrical output and, on the other hand, economies of scale related to capital investments, the costs per unit MWh produced are relatively high for this sugarcane mill.

The LCOE in SC100 is lower than in SC70 for almost all sugarcane mills. The reasonable explanation for this is that more straw is available for electricity generation in SC100. Due to scale economies, the costs per MWh produced decrease with increasing electrical output. The percentage change of LCOE between the scenarios is highest for sugarcane mills that also have to invest in a connection to the grid. Only Paramonga has a slight increase in LCOE in SC100. This is because the increase in plant scale and electrical output for Paramonga in SC100 is lower than for the other sugarcane mills. The increase in scale and electrical output is not high enough to obtain lower costs per MWh produced.



Figure 11. LCOE results in €/MWh for each sugarcane mill in SC70 and SC100.

Values above data columns represent the percentage change in LCOE between SC70 and SC100.

Figure 12 depicts the cost-supply curves of the LCOE of electricity generation from straw. The electric output in SC70 at the respective LCOE is first shown, followed by the electric output and LCOE in SC100. For instance, the electric output of Casa Grande amounts to 216 GWh/y in SC70 at 78.45 \in /MWh and 264 GWh/y in SC100 at 77.33 \in /MWh. Whereas it is common in cost-supply curves to depict supply in the order of increasing costs, it is decided to first depict the potential supply in SC70 followed by supply in SC100 since this would be the logical order regarding the increased employment of mechanical harvesting. Paramonga has the lowest LCOE, but Casa Grande shows the highest potential of electrical output. However, it can be observed in Figures 11 and 12 that none of the sugarcane mills can generate electricity below the bioelectricity cut-off price of 52 \in /MWh. Hence, using straw for local bioelectricity generation is considered not to be an economically feasible option for sugarcane mill operators.



Figure 12. Cost-supply curve of electricity generation from straw.

The potential electricity generation in SC70 and SC100 is depicted at the respective LCOE for each sugarcane mill.

4.5 Sensitivity analysis

4.5.1 GHG performance

The sensitivity of the GHG performance of bagasse pellets is investigated in a best and worst case scenario, which entail situations that are respectively optimistic and pessimistic regarding the GHG performance. The assumed base case scenario represents the results in GHG emissions as presented in section 4.2.

The base case did not take into account potential (negative) GHG emissions from soil carbon stock changes, either as a result of improved agricultural practices or from land-use change. The RED II states that these negative emissions should be taken into account if increased soil carbon content compared to a reference situation can be proved or when it is reasonable to expect that soil carbon content has increased over the period that raw materials were cultivated (EC, 2018c). Multiple reference scenarios could be assumed for the case of straw, such as leaving all straw on the field or the pre-harvest burning of sugarcane fields. When assuming a reference situation of leaving all straw on the field, a decrease in soil carbon content could be the result when a share of straw is removed for energy purposes. However, if a reference situation of pre-harvest burning practices is assumed, the soil carbon content could increase when a share of straw remains on the field for agro-ecological purposes. The decrease in soil carbon stock is assumed in the worst case scenario and increase in soil carbon stock is assumed in the worst case scenario and increase in soil carbon stock is assumed in the worst case scenario and increase in soil carbon stock in the best case scenario.

The GHG emissions from soil carbon stock changes are calculated with eq. (2) (section 2.6). Whereas the difference in carbon stock per unit area in the reference and actual land-use situation (respectively CS_R and CS_A) should be measured, methodologies exist for calculating this value. It is assumed that the difference of carbon stock per unit area is composed of 50% of the carbon content of straw remaining on the field. Note that this is a simplified assumption since the actual soil carbon dynamics are more complex (Buchspies et al., 2020). The assumed 50% is based on the share of organic matter that remains left on the field (not decomposed material) after one year, based on the methodology applied by Buchspies et al. (2020).

Furthermore, the stages with a significant contribution to total GHG emissions are straw collection, pre-treatment, deep-sea shipping and end-use. It is expected that used input data for straw collection will not vary that much in practice. GHG emissions of the pre-treatment stage are mainly due to emissions from electricity consumption, calculated with the emission factor of the electricity mix in Peru of 263 gCO_{2eq} per kWh, as reported by Brander et al. (2011). As a result of the stimulated employment of renewable energy generation in Peru (especially hydro, wind and solar), renewable electricity has steadily increased in the national electricity mix during the last decade and is expected to further increase in the coming years (Osinergmin, 2019). Hence, it is expected that the reported emission factor based on data in 2011 has decreased in the meantime and will decrease further in the future. The worst case scenario assumes a slight variation of +5% of the grid electricity emission factor since it is not expected that the emissions factor will be much higher than its initial value. The best case scenario assumes that renewable electricity generation (especially hydroelectricity) in Peru will increase to a situation comparable to Brazil. The emissions factor of grid electricity in Brazil is 93 gCO_{2eq} per kWh (Brander et al., 2011), which would mean a variation of -65%. A more conservative variation of -50% of the initial value is assumed in the best case scenario. Additionally, the GHG emissions from electricity consumption in the end-use stage cause the significant contribution to total GHG emissions. The contribution of renewable electricity in the Dutch electricity mix is expected to increase in the coming years to achieve national climate targets (Klimaatberaad, 2019), leading to a decrease in the emission factor of grid electricity. A variation of +5% and -30% of the Dutch grid electricity emission factor is assumed in respectively the worst and best case scenario. Finally, HFO consumption for deepsea shipping has some uncertainty, depending largely on navigation speed (Stopford, 2008). Mai-Moulin et al. (2017) used a variation of $\pm 25\%$ for transport cost factors. It is, however, expected that the range in HFO consumption will not deviate from the initial value to such an extent. Therefore, a smaller variation of $\pm 15\%$ for HFO consumption is applied. The assessed variation in parameters for the sensitivity analysis of the GHG performance are summarised in Table 7.

Parameter	Best case	Worst case
Carbon stock changes	+50% of carbon content in	-50% of carbon content in
	straw remaining on the field	straw remaining on the field
Peruvian grid electricity emission factor	-50%	+5%
Dutch grid electricity emissions factor	-30%	+5%
HFO consumption	-15%	+15%

Table 7. Variation in parameters in the sensitivity analysis of the supply chain GHG emissions.

The results of the assessed sensitivity cases for the region Piura are depicted in Figure 13 (La Libertad and Lima show similar results). The GHG emissions from processes that are largely affected by the varied parameters are depicted, i.e. soil carbon stock, electricity consumption in the pre-treatment stage, electricity consumption in the end-use stage and HFO consumption for deep-sea shipping. Figure 13 shows the combined effect of changing parameters on the GHG emissions per MJ electricity generated at the Amer. The worst case scenario shows an increase of 22% and 27% in GHG emissions in SB and FBS respectively. The difference for the best case scenario is slightly higher with a decrease of 35% and 34% in respectively SB and FBS. Whereas the worst case scenario assumed a low variation of the grid electricity emission factor in Peru and the Netherlands, it is particularly remarkable that this scenario still shows a significant increase in GHG emissions. This can be ascribed to the emissions from decreased soil carbon stock. In the best case scenario, the reduction in GHG emissions can be mostly ascribed to the negative GHG emissions from increased carbon stock.

Figure 14 depicts the GHG savings of electricity generation from bagasse pellets for the sensitivity cases. Even in the worst case scenario, the bagasse pellets still amply comply with the Dutch GHG target of 70% GHG savings. Therefore, it can be stated that the bagasse pellets from Peru show much potential as biomass fuel for power plants in the Netherlands in terms of GHG performance. It is more

likely that bagasse pellets comply with a target of 80% GHG savings in the best case scenario, however, the opposite holds for the worst case scenario. It is important to note here that the worst and best case scenarios represent two extremes, which means that it is more likely that in practice, the GHG savings will resemble those of the base case scenario.



Figure 13. Results of sensitivity cases for Piura region.

The GHG emissions per MJ electricity generated are depicted for the base, worst and best case scenarios. The percentages depict the difference between either the worst and best case scenario, compared to the base case scenario.



Figure 14. GHG emissions savings of electricity generation for the sensitivity cases.

4.5.2 Cost performance

The major contributing stages to the total pellet costs consist of surplus bagasse collection, straw collection, pre-treatment and deep-sea shipping. The costs at which feedstock (i.e. bagasse and straw) could be obtained depend on e.g. supply and demand market forcing and electricity prices (for bagasse-generated electricity). The uncertainty of feedstock costs is assessed by applying a variation of $\pm 25\%$ of the original value, as applied by Mai-Moulin et al. (2017). Another parameter with a large degree of uncertainty is composed of the pre-treatment costs. Visser et al. (2020b) point out that pre-treatment costs in wood pellet studies vary with a factor 10 difference, which is mostly ascribed to the effect of different plant scales. From the pilot of RWE and Raízen, it is found that especially the OPEX and personnel costs can significantly differ from the expected value, which is partly ascribed to the fact that certain cost parameters are country-specific (M. Bouwmeester – RWE, personal communication, 29 October, 2020). Altogether, the CAPEX, OPEX and personnel costs are varied with a relatively large range of $\pm 50\%$, as assumed by Mai-Moulin et al. (2017). Finally, the HFO consumption for deep-sea shipping is again varied with $\pm 15\%$. The applied variations in parameters for the sensitivity analysis of the supply chain costs are presented in Table 8.

Parameter	Unit	Original value	Variation	Variation rate
Surplus bagasse costs	€/tonne bagasse (MC 50%)	9.31	6.99 – 11.64	±25%
Straw farmgate costs	€/tonne straw (MC 15%)	16.63	12.47 – 20.79	±25%
Pre-treatment costs - CAPEX - OPEX - Personnel	€/tonne pellet	9.71 20.18 2.34	4.86 - 14.57 10.09 - 30.28 1.17 - 3.51	±50%
HFO consumption - Handysize - Supramax	gHFO/(tonne*km)	2.49 1.61	2.11 – 2.86 1.37 – 1.85	±15%

Table 8. Variation in parameters in the sensitivity analysis of the supply chain costs.

The sensitivity analysis is again only performed for the SB and FBS scenarios. The result for the regions Piura and Lima are depicted in Figure 15 in a spider diagram. The spider diagram of La Libertad resembles the one of Piura and is therefore not shown. The solid and dashed lines depict the results of respectively the SB and FBS scenario. In general, it can be observed that HFO consumption only has a slight influence on pellet costs compared to the other parameters. Varying surplus bagasse costs has more impact on pellet costs in SB than in FBS. This is because the share of surplus bagasse in total bagasse availability is lower in FBS since a share is constituted by the freed up bagasse. Therefore, a fluctuation in costs of surplus bagasse has a lower impact on the pellet costs in FBS. In FBS, bagasse is freed up by using straw in the boiler of the sugarcane mill. The bagasse pellet costs in FBS are therefore more sensitive to the straw farmgate costs. The total pellet costs in both SB and FBS are most sensitive to the range in pre-treatment costs.

From the spider diagram of Lima, it can be observed that bagasse pellet costs are more sensitive to changing pre-treatment costs in SB compared to FBS, which is denoted by the steeper slope of pre-treatment costs in SB (Figure 15). The main reason for this can be that Lima has the highest increase in bagasse pellet supply potential between SB and FBS of a factor 2.8, compared to Piura and La Libertad with a factor 2.4 and 1.5 respectively. Moreover, Lima has a relatively low pellet supply potential, resulting in less benefit from economies of scale. With the low pellet supply and low scale economies in SB, the total pellet costs are relatively more sensitive to variations in pre-treatment costs.



Figure 15. Sensitivity of bagasse pellet costs for the regions Piura and Lima. The costs in SB are depicted by solid lines and the costs in FBS are depicted by dashed lines.

4.5.3 LCOE of straw for local bioelectricity

The sensitivity of the LCOE is analysed by assessing the uncertainty of various parameters. First, literature indicates different values for the amount of straw that should remain on the field for agroecological purposes (Cardoso et al., 2015; Cervi et al., 2019a). A variation of 30% to 70% of produced straw that should remain on the field is assessed in the sensitivity analysis, as applied by Cardoso et al. (2015). Furthermore, the electrical conversion efficiency of the power plant is varied from 20 to 35%, as indicated by Cervi et al. (2019a). Then, a common uncertain value used in cost assessments is the discount rate, which is assumed at 12%. The variation of \pm 30% applied by Cervi et al. (2019b), based on debt financing options of Brazilian electricity projects, is used. Finally, the CAPEX and OPEX of the power plant are uncertain parameters subjected to e.g. annual inflation and exchange ratios of imported equipment. Seabra and Macedo (2011) and Cervi et al. (2019b) used a variation rate of \pm 20% for the FCI and OPEX. It is assumed in this research that a new power plant has to be built to process all sustainably available straw, whereas in practice only existing equipment in the sugarcane mill potentially has to be replaced. The investment and operational costs could thus be significantly lower in reality. Therefore, a variation of -50 to +20% of the FCI and OPEX is assumed. The applied variations in parameters for the sensitivity analysis of the LCOE are presented in Table 9.

Parameter	Unit	Original value	Variation	Variation rate (% of original value)
Straw remaining on field	tonne/ha	7.5	30 – 70% (of obtained straw)	-30 - 60%
Electrical conversion efficiency	%	25	20 – 35	-20 - 40%
Discount rate	%	12	8.4 - 15.6	±30%
CAPEX: FCI	million €	57.6	28.8 - 69.1	-50 – 20%
OPEX	(million €*MW)/y	0.19	0.09 - 0.23	-50 – 20%

Table 9. Variation in parameters in the sensitivity analysis of the LCOE.

Only the LCOE in the SC100 scenario is assessed since the LCOE is similar in SC70 and SC100 and no significant differences between these scenarios are expected in the sensitivity analysis. The results of the LCOE sensitivity of the Caña Brava sugarcane mill are depicted in Figure 16. The assessed sensitivity of the other eight sugarcane mills show a similar diagram. Varying the amount of straw that should remain on the field has no significant effect on the LCOE. The electric conversion efficiency has some significant influence on the LCOE, as well as the discount rate. The steep slope of the FCI and OPEX parameter shows the most significant influence on the LCOE with a range of 46-91 €/MWh for Caña Brava. If the FCI and OPEX are about -40% of the initial value, electricity at the Caña Brava sugarcane mill could potentially be generated below the bioelectricity cut-off price of 52 €/MWh. However, a decrease of 40% in assumed FCI and OPEX is quite vigorous and it is not expected to be likely that these costs will be that much lower in reality than the assumed values. Therefore, it can be stated that it is highly unlikely that there is an economically feasible business case for the local use of straw for bioelectricity generation. The FCI and OPEX are the main determinants of the business case, which should be determined on a case-by-case basis.



Figure 16. LCOE sensitivity of the Caña Brava sugarcane mill.

5 Discussion

This research has assessed the GHG and cost performance of bagasse pellets from Peru with end-use in the Amer Bio CHP in the Netherlands. It is important to note that the studied supply chain does not yet exist and the GHG and cost assessments are performed to explore the potentials of the theoretical supply chain. This section discusses the implications of methodological choices of this research and the prospects of future demand for sugarcane residues.

5.1 Implications of methodological choices

5.1.1 Bagasse supply potential

The volumes of available bagasse are determined based on assumptions regarding surplus bagasse and bagasse that could be freed up. Surplus bagasse is assumed to be 33% of total produced bagasse at the sugarcane mill, based on a LCA study of a Brazilian sugarcane mill by Lopes et al. (2014). It is questionable whether this share also holds for Peruvian sugarcane mills. In Brazil, bioelectricity generation from sugarcane residues has been growing in the last decades and sugarcane mill operators have increasingly invested in efficiency measures to reduce the energy consumption of processes in the sugarcane mill (Bajay, 2011; Dos Santos & Ramos, 2020). It is unclear whether Peruvian sugarcane mill operators have similarly invested in efficiency measures. Hence, the 33% could be an overestimation and the total bagasse pellet supply potential from surplus bagasse (SB scenario) of 5.1 PJ could in reality be lower. On the other hand, the potential volumes for freeing up bagasse by implementing improvements at the sugarcane mill could subsequently be higher than assumed. This research assumed shares for freeing up bagasse that were found during the pilot of RWE and Raízen. The assumed share of 5% for freeing up bagasse by improvements can be higher for Peru since there could be much room for improvement. In general, the current course of processes and state of equipment should be examined for each Peruvian sugarcane mill individually to determine a more precise supply potential.

Furthermore, some practical limitations and risks need to be considered regarding bagasse availability. The supply chain with bagasse supply from Peru is currently theoretical and sugarcane mill operators should be approached to set up the supply chain. It is questionable whether sugarcane mill operators are willing to engage in a new collaboration for supplying surplus bagasse and freed up bagasse, where the latter requires adjustments in their sugarcane mills. Especially the technical limitations of employing straw in originally bagasse-fired boilers constitute a risk factor which could impede the willingness of sugarcane mill operators to collaborate. In Brazilian sugarcane mills, straw is increasingly employed in boilers but is always mixed with a larger share of bagasse to reduce damages in the boiler (Leal et al., 2013). An alternative approach to reduce risks is to wash straw before combustion in the boiler, which is currently tested by researchers from Wageningen University & Research (WUR) (WUR, n.d.). Whereas the risks of straw combustion are often highlighted in literature, specific methods to minimise or avoid the technical limitations of straw combustion should be further developed and tested in future research (Cervi et al., 2019a; Leal et al., 2013). Although straw combustion could negatively affect core operations in the sugarcane mill (e.g. plant downtime due to technical difficulties), the use of straw for freeing up bagasse that can be sold to third parties provides economic benefits for sugarcane mill operators. These factors could influence the willingness of sugarcane mill operators to collaborate for bagasse supply. In a follow-up study, Peruvian sugarcane mill operators should be approached by parties with a demand for bagasse to negotiate the possibilities for a collaboration, so that a realistic bagasse supply potential could subsequently be estimated.

5.1.2 Straw collection

The amount of straw that should remain on the field for agro-ecological purposes is assessed in the sensitivity analysis of the LCOE of straw for local bioelectricity generation. The results show that this

parameter influences the electrical output, but does not have a significant influence on the LCOE. In addition, it is found that there is no economically feasible business case of using straw for local bioelectricity generation. For the use of straw in the bagasse pellet supply chain, straw is assumed to be collected from the entire stretch of the sugarcane fields and transported to the sugarcane mill and pellet plant. In practice, straw would be collected from the fields most nearby the location of use to minimise the transport distance. Due to the minimal contribution of the straw transport stage in the GHG emissions and costs (Figures 6 and 8 respectively), the collection of straw from nearby fields will have an insignificant effect on the outcomes. Yet, it is important to understand how much straw could be removed from the most nearby sugarcane fields to have enough remaining on the field. Values provided in literature are based on field experiments on sugarcane fields in Brazil (e.g. Hassuani et al., 2005; Michelazzo, 2005). The conditions in Brazil are, however, not similar to Peru and it is suggested by Cervi et al. (2019a) that the required amount of straw remaining on the field should be assessed at field level, taking into account factors such as soil, meteorological and topographic characteristics. Therefore, field experiments on Peruvian sugarcane fields are recommended for future research to address these agro-ecological factors. This way, a representable value for straw that should remain on Peruvian sugarcane fields specifically can be determined. Alternatively, research is being conducted on removing large volumes of straw from the field, washing out the nutrients at the sugarcane mill and transporting the nutrients back to the field through irrigation systems (WUR, n.d.). Since most sugarcane fields in Peru are irrigated, this procedure could have much potential for removing the maximum possible amount of straw from the field for energy purposes while preserving the nutrients required for fostering sugarcane production. If the results of experiments with this procedure are promising, this procedure could be tested on Peruvian sugarcane fields.

5.1.3 GHG assessment

The supply chain GHG emissions are calculated with the method provided by the RED II. The (negative) GHG emissions from potential carbon stock changes, which depends on the assumed reference situation, are assessed in the worst and best case scenario in the sensitivity analysis. There is a significant difference in GHG savings between these scenarios, meaning that the chosen reference situation has a major impact. For instance, bagasse pellets from Piura in SB obtain GHG savings of 80% and 87% in respectively the worst and best case scenario. In FBS, the GHG savings in these scenarios are respectively 76% and 84%. Besides the assumed pre-harvest burning practice and leaving all straw on the sugarcane fields as reference situations, an alternative reference situation can be assumed in which sugarcane mill operators would already remove a share of the straw, since the high layers of straw on the field impede sugarcane yields (Hassuani et al., 2005). This reference is represented by the base case scenario, in which there is no difference in terms of carbon stock changes when removing a share of straw for either energy purposes or for fostering sugarcane yields. Another possible reference situation traces back to the land-use purposes before the cultivation of sugarcane. Desert areas in northwest Peru have been transformed into sugarcane fields (Nolte, 2019). It could reasonably be expected that the soil carbon stock has increased in these areas due to the transformation into fertile agricultural land. This reference situation is not considered in the sensitivity analysis.

The RED II indicates that potential negative GHG emissions from improved agricultural management practices (e_{sca} in eq. (1)) should be proved with measurements of soil carbon content (EC, 2018c). The first measurement (i.e. the reference situation) should be in advance of the feedstock cultivation. The moment of this first measurement in case of straw is rather unclear, which could either be the moment before sugarcane cultivation, before useful straw production (i.e. pre-harvest burning) or before collecting straw for energy purposes (i.e. all straw remaining on the fields). Furthermore, the reference situation for calculating emissions from carbon stock changes due to land-use change (e_l in eq. (1)) is represented by the land-use in January 2008 or by land-use 20 years before raw material was obtained, whichever was the later (EC, 2018c). The specific land-use and carbon stock in January 2008 (which is later) thus has to be determined for each sugarcane field. It is, however, not expected that information is available on the specific carbon stock at that time. Moreover, it is questionable whether land-use change emissions should be considered at all for agricultural residues, especially since the productivity of the crop P in eq. (2) for calculating land-use change emissions could rather refer to the productivity of bioenergy crops. In summary, the appropriate method for taking into account (negative) GHG emissions from carbon stock changes in the case of agricultural residues remains unclear. Guidelines on the appropriate method should be further clarified and improved in the future (e.g. in a successor of the RED II).

Bagasse is considered an agricultural residue in the GHG assessment, for which the RED II indicates that GHG emissions before collection do not have to be taken into account since residues are not the primary aim of a production process (EC, 2018c). However, Cervi et al. (2019a) discuss that recently built Brazilian sugarcane mills recognise bioelectricity generation from bagasse and straw as a core business model besides ethanol and sugar production. In this sense, bagasse can be defined as a coproduct of sugarcane production instead of a residue, for which GHG emissions do have to be taken into account through allocation procedures (EC, 2018c). In general, Peruvian sugarcane mills are rather old and are indicated to have much potential for improving electricity generation from bagasse (Perúcaña, 2019). It is therefore not expected that these sugarcane mills currently envision bagassegenerated electricity as core business, which makes the consideration of bagasse as agricultural residue reasonable. On the other hand, the removal of straw for freeing up bagasse could have significant impacts on the core business of sugarcane cultivation, for instance due to its effect on soil nutrient recycling and irrigation requirements. It would be reasonable to allocate a share of GHG emissions from sugarcane cultivation to the collection of straw due to the implications of straw removal. Commonly applied allocation methods are based on energy or mass basis (e.g. Vera et al., 2019). Allocation of emissions for the use of straw would mostly affect the GHG performance in the FBS scenario, but the effect is expected to be limited. It is still expected that bagasse pellets will comply with the Dutch GHG target, but it would become less likely that bagasse pellets in FBS will obtain 80% GHG savings. Whereas this research did not include GHG emissions before agricultural residue collection, it should always be considered in future supply chain studies whether it is reasonable to not take into account these GHG emissions when considering bagasse and straw. Furthermore, the method for assessing the sustainability of agricultural residues could be subjected to change in the future, which could have a major impact on the GHG performance. This is further addressed in section 5.2.3.

5.1.4 Supply chain optimisation

Since the assessed bagasse pellet supply chain is currently theoretical, the supply chain is set up in a way that optimises the GHG and cost performance of bagasse pellets. Certain optimisation options are only considered to a limited extent or not considered at all. For instance, optimising pellet plant locations leads to an optimisation in both GHG and cost performance. The pellet plant locations are roughly estimated based on the location of sugarcane mills and export terminals and the on-land transport routes. Since only nine sugarcane mills are considered, this approach is found sufficient to get an indication of optimal pellet plant locations. However, if many more sugarcane mills of varying capacity are considered in a case study, this approach can be too simplistic and insufficient. In such cases, it is recommended to consider alternative methods such as spatial optimisations with ArcGIS (e.g. Lin et al., 2013) or linear optimisation models (e.g. Jonker et al., 2016), which allow for determining the optimal number, capacity and locations of a facility where raw material is processed or converted.

Furthermore, the results showed that the Supramax vessel for deep-sea shipping provides benefits in terms of GHG emissions and costs compared to Handysize vessels. The option of transporting all bagasse pellets to the port of Callao (Lima) from where a Supramax vessel can be employed can reduce

the GHG and costs of the deep-sea shipping stage. However, transporting bagasse pellets to one export terminal leads to higher on-land transport GHG emissions and costs. This could level out the effect of reduced GHG emission and costs of deep-sea shipping and could even lead to increased total GHG emissions and costs. In general, it is not expected that exporting bagasse pellets from one export terminal with a larger vessel would significantly improve the GHG and cost performance.

Literature indicates potential improvements in GHG and cost performance by introducing an additional pre-treatment step, such as the torrefaction of biomass pellets (Visser et al., 2020a). A drawback is that the application of torrefied pellets is limited to thermochemical conversions since biochemical conversion of torrefied pellets is not feasible. The bagasse pellets for electricity and heat generation already comply with the Dutch GHG target, so the option of torrefaction for this end-use purpose is only relevant if the cost performance would be significantly improved. The higher energy density of torrefied pellets reduce transport costs, but the torrefaction process increases pellet production costs (Visser et al., 2020a). Future research could assess the effect of torrefaction on the cost performance of bagasse pellets from Peru. If bagasse pellets would have another end-use purpose than thermochemical conversion, the option of torrefaction would not be relevant.

5.2 Demand prospects for sugarcane residues

5.2.1 Local demand

Besides the limitations of available surplus bagasse and freed up bagasse from the side of the sugarcane mill, the availability is also limited by the local demand for bagasse by other industries, such as the paper and pulp industry. The potential local demand for bagasse by this industry is not assessed in this research, however it is stated that this sector is rather underdeveloped in Peru (Moncada et al., 2014). The demand for bagasse by this industry is therefore expected to be limited.

Alternatively, there could be a demand for bagasse and straw for the conversion into bio-based products in lignocellulosic-based biorefineries. The conversion of lignocellulosic biomass in biorefineries is currently in a developmental stage. Due to a lack of efficient and low-cost technologies, production costs in such biorefineries are currently high and the return on investments is rather low (Pérez et al., 2017). Yet, lignocellulosic feedstock for biorefineries is considered to have an advantage compared to other biomass feedstock due to limited competition with food crops (Escobar et al., 2009). Therefore, the development of lignocellulosic-based biorefineries is increasingly facilitated in for instance the EU strategy towards a bio-based economy (EC, 2018b). There is currently no national policy in Peru towards the promotion of a bio-based economy, nor are there any developments in Peru of bio-based materials from lignocellulosic feedstocks (H. Davila – Coazucar, personal communication, 29 October, 2020). However, the setup of a bagasse pellet supply chain mobilises sugarcane residues from sugarcane mills, which could stimulate the local demand for these residues for e.g. high-value applications in biorefineries. This way, the supply chain can stimulate local initiatives and economic activity in the bio-based products industry, which creates an opportunity for the development of a bio-based economy in Peru.

5.2.2 Straw for local bioelectricity generation

The business case of straw for local bioelectricity generation in the Peruvian sugarcane mills is currently not economically feasible. Only if the FCI and OPEX end up to be much lower than expected or if the bioelectricity cut-off price would be higher than assumed (not assessed in the sensitivity analysis), a business case could, in theory, become economically feasible. However, the question arises whether bioelectricity from straw could compete with other renewables (e.g. hydro, solar and wind) for electricity generation. Currently, hydroelectricity has the largest share in renewable electricity generation in Peru, followed by wind and solar (Osinergmin, 2019). During the fourth renewable energy auction, the costs for electricity generation from renewables were $34-46 \notin$ /MWh for hydro, $39-52 \notin$ /MWh for wind and $43-44 \notin$ /MWh for solar. Considering the LCOE of $68-107 \notin$ /MWh

(in SC100) of bioelectricity from straw, there is only potential if large subsidies would be awarded. This is currently not the case and not expected to be so in the near future. Hence, straw for local bioelectricity generation is not economically feasible. It is therefore recommended to Peruvian sugarcane mill operators to consider the alternative uses of straw, such as for freeing up bagasse.

5.2.3 Demand in the Netherlands

The results of this research show that electricity and heat generation from bagasse pellets in an enduse facility in the Netherlands complies with the Dutch GHG target of 70% GHG savings. If the end-use of bagasse pellets in other facilities starting operations from 2026 is considered, it becomes challenging to comply with the target of 80% GHG savings, as set by the RED II. The results in cost performance show that bagasse pellets are competitive with wood pellets. Moreover, bagasse pellets show considerable potential for substituting wood pellets since the use of woody biomass for bioenergy is currently heavily debated in the Netherlands (Strengers & Elzenga, 2020). Using pellets made from sugarcane residues for electricity and heat generation could be more socially accepted than the use of wood pellets. However, the cost-competitiveness of electricity generation from biomass pellets in general compared to other (renewable) sources is questionable. Biomass pellet prices for converted coal-fired power plants have to reduce to such an extent that competition with gas-fired power plants (including CO₂ penalty) is possible (M. Bouwmeester – RWE, personal communication, 29 October, 2020). The relatively high costs of biomass pellets for electricity generation could lead to a reliance on subsidies.

Whereas the SDE+⁸ subsidy was awarded to RWE for the period 2018-2026 as support for increasing biomass co-firing rates, it is not expected that a new subsidy will be granted for electricity and heat generation from biomass. This is because the government has recently announced plans to phase out the support of low-value applications of biomass such as electricity and heat generation (Van Veldhoven & Wiebes, 2020), in accordance with a recent advisory report from the *Sociaal-Economische Raad* (socio-economic council) (SER)⁹. In response to the ongoing social-political debates on the sustainability of biomass for bioenergy in the Netherlands, the SER was asked by the Dutch cabinet to advise on a sustainability framework for the use of biomass. The SER underlines that biomass should be reserved for high-value applications in e.g. the bio-based products sector and envisions a significant increase in the demand for biomass feedstock by this sector in the coming years (SER, 2020).

The expected growing demand for lignocellulosic feedstock for bio-based products has stimulated research on the performance of local biorefineries. For instance, Vera et al. (2019) investigated the GHG performance of lignocellulosic feedstock for a multi-output biorefinery in the Netherlands. It was found that internationally sourced feedstocks for ethanol production are currently unable to comply with the strict GHG criteria set by the RED II. However, it is indicated that the method provided by the RED II for calculating GHG emissions falls short since the challenges of emission allocations in multi-output refineries are not addressed. On the other hand, high GHG savings were found for lactide production in the biorefinery. Vera et al. (2019) conclude that there is much potential for improvement of the environmental performance of biorefineries by technological development, which is recommended as a focus area for future research.

The developing bio-based products industry in the Netherlands is constituted of various companies focused on producing bio-based materials or chemicals (e.g. Avantium, n.d.) and clusters of initiatives

⁸ The *Stimulering Duurzame Energieproductie* (promotion renewable energy production)+ (SDE+) was introduced in 2011 as a national subsidy scheme for the promotion of investments in renewable energy technologies (RVO, n.d.).

⁹ The SER is an independent advisory council that supports the Dutch cabinet and parliament in providing advice on socio-economic subjects for policy making.

where stakeholders such as companies, municipalities and knowledge institutes collaborate (e.g. Biobased Delta, n.d.). Through continuing scientific research, developments and governmental (financial) support, this sector could reach a stable and growing demand for biomass feedstock in the future. The supply of bagasse pellets from Peru for could then become relevant for this industry. The SER stresses the need for more stringent sustainability criteria for biomass feedstock supply chains and suggests among others that as little as possible distinction between primary and residual products of processes should be made (SER, 2020), which contradicts the method from the RED II. As explained in section 5.1.3, this could have a significant effect on the GHG performance of bagasse pellets and their potential use in the bio-based products sector. Whereas it is important to define environmental criteria could impede developments towards a bio-based economy. Policymakers should therefore compose a clear strategy for the role and support of biomass, which should be based on objective scientific studies and advisory reports and should both ensure the sustainability of biomass and foster developments towards a bio-based economy.

Following the developments in the Dutch policy of biomass support, bagasse pellets from Peru can be used for electricity and heat generation in existing facilities in the Netherlands in the coming years. On the long term, the potential end-use of bagasse pellets is expected to shift to the bio-based products sector in the Netherlands and later on, in other countries (e.g. Peru, as described in section 5.2.1). In summary, bagasse pellets are envisioned to have a role in electricity and heat generation in the short run, which will transition to a significant role in the bio-based products sector in the long run.

6 Conclusion

This research assessed the GHG and cost performance of a bagasse pellet supply chain, considering bagasse sourced from Peru and end-use of bagasse pellets in the Amer Bio CHP in the Netherlands. The potential bagasse supply is determined in three scenarios: 1) surplus bagasse (SB), 2) surplus bagasse and freed up bagasse by implementing improvements at the sugarcane mill (FBI) and 3) surplus bagasse, freed up bagasse from improvements and freed up bagasse by using straw in the boiler of the sugarcane mill (FBS). The method from the RED II is used to calculate the GHG savings and to determine whether bagasse pellets comply with GHG emission reduction criteria. The cost performance is evaluated by comparing bagasse pellet costs to average industrial wood pellet prices and wood pellet supply chain studies.

The results show that bagasse pellets in the SB, FBI and FBS scenarios comply with the Dutch GHG target of 70% GHG savings, which is required for the use of biomass pellets in the Amer. If the use of bagasse pellets in installations starting operations from 2026 is considered, it could become challenging to comply with the RED II target of 80% GHG savings, which applies for such installations. The GHG performance of bagasse pellets is comparable to U.S. sourced wood pellets. Assuming different reference scenarios in taking into account potential (negative) GHG emissions from soil carbon stock changes is found to have a significant influence on the outcomes in GHG performance. Nevertheless, even in the assumed worst case scenario the bagasse pellets still comply with the Dutch GHG target. Guidelines on the appropriate method to account for emissions from carbon stock changes in the case of agricultural residues should be further clarified in the future.

The bagasse pellet costs are calculated to be lowest in the SB scenario (6.7-8.2 \notin /GJ), which is closely followed by FBI (6.8-8.2 \notin /GJ). The pellet costs in SB and FBI show much potential to outcompete wood pellets. Bagasse pellet costs in FBS are significantly higher (8.8-9.2 \notin /GJ) but are still found to be competitive with wood pellets. The economic supply potential of bagasse pellets in the SB, FBI and FBS scenarios is respectively 5.1, 6.0 and 9.0 PJ/y. Assumed values for determining the supply potential are based on experiences in the Brazilian sugarcane industry (e.g. pilots in sugarcane mills, values reported in literature). Future research should focus on factors for mobilising sugarcane residues in Peru, such as the amount of straw that should remain on the sugarcane fields for agroecological purposes and the potentials for freeing up bagasse at the sugarcane mill. This way, a more representative bagasse pellet supply potential from Peru can be determined.

Besides the use of straw for freeing up bagasse, the possibility of using straw locally for bioelectricity generation at the sugarcane mill is assessed to determine its economic feasibility. It is found that the costs of using straw for local bioelectricity generation are much higher than the bioelectricity cut-off price of 52 \in /MWh and cannot compete with the low costs of electricity generation from other renewables (e.g. hydropower). Therefore, straw for local bioelectricity generation is not considered to be economically feasible.

This research shows that bagasse pellets from Peru show much potential as biomass fuel for electricity and heat generation in an existing power plant in the Netherlands, considering the GHG and cost performance. This potential is expected to gradually transition towards applications in the bio-based products sector as a result of supporting national policy towards a bio-based economy. Furthermore, the mobilisation of bagasse and straw could stimulate local initiatives for developing a bio-based economy in Peru in the long run. Policymakers in the Netherlands have a major role in composing a strategy for biomass, in which criteria for ensuring biomass sustainability and efforts to foster developments towards a bio-based economy should be well-balanced.

7 References

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Appendix A: Detailed maps of sugarcane regions

Detailed maps of the sugarcane cultivation areas are depicted in Figure A1. Orange triangles depict the sugarcane mills, yellow circles depict export ports and yellow circles containing a black dot depict ports that are selected as export ports where bagasse pellets are potentially exported from.



Figure A1. Detailed maps of sugarcane cultivation regions in Peru.

Appendix B: CPI and currency conversion

Table A1 presents the applied CPIs for US dollar (USD), euro, Brazilian real (BR) and Peruvian sol (PEN). The following rates are applied for conversion to euros: $0.85 \notin$ /USD, $0.23 \notin$ /BR and $0.26 \notin$ /PEN (Exchange Rates, n.d.).

Year	USD ¹	Euro ²	BR ³	PEN ³
2004	188.90	81.00	53.78	86.45
2005	195.30	82.75	57.48	87.74
2006	201.60	84.58	59.88	88.74
2007	207.30	86.55	62.06	92.26
2008	215.30	89.72	65.59	98.36
2009	214.54	90.60	68.79	98.59
2010	218.06	92.49	72.26	100.64
2011	224.94	95.36	77.06	105.42
2012	229.59	97.88	81.22	108.21
2013	232.96	99.35	86.26	111.30
2014	236.74	99.90	91.72	114.89
2015	237.02	100.00	100.00	119.95
2016	240.01	100.25	108.74	123.83
2017	245.12	101.96	112.49	125.51
2018	251.11	103.89	116.61	127.22
2019	255.66	105.42	120.96	128.95

Table A1. Consumer price index of USD, euro, BR and PEN.

Sources: [1] US Inflation Calculator (n.d.), [2]Eurostat (n.d.), [3] St. Louis Fred (n.d.).

Appendix C: Elaborate data inventory

General data

Emission factors, LHVs, general cost data and assumed weight losses in the supply chain are presented in Tables A2-A5. As mentioned before, the used emission factors of biomass fuels include N_2O and CH_4 emissions and exclude CO_2 emissions, which is in line with the CO_2 neutrality of biomass combustion (EC, 2018c). The biomass fuel emission factors are calculated following the method used by Derks (2018). Labour costs (Table A4) are specified for the transport and manufacturing sector, using the respective average wages in Peru for these sectors. Labour costs for transport are used in the transport stages and labour costs for manufacturing are used in the pre-treatment stage.

	Value	Sources and notes
Fuels	gCO _{2eq} /MJ	
Diesel	95.1	1
HFO	94.2	1
MDO	94.2	1
Biomass fuels	gCO _{2eq} /kg	
Bagasse (50% MC)	13.2	а
Bagasse pellet (10% MC)	23.7	а
Straw (15% MC)	22.6	а
Grid electricity	gCO _{2eq} /MJ _e	
Peru	73.1	2
The Netherlands	183.0	1

Table A2. Emission factor of transport fuels, biomass feedstock and grid electricity.

<u>Sources</u>: [1] Giuntoli et al. (2017), [2] Brander et al. (2011). <u>Notes</u>: a. 1.55% of GHG emissions from biomass combustion are due to N_2O and CH_4 (Hanssen et al., 2017). Emission factor is calculated with 44/12=3.7 gCO₂ emitted per g C and a carbon content of 41% and 39% in respectively bagasse and straw (Seabra et al., 2010).

Table A3. LHV of biomass feedstocks and fuels.

	Value (MJ/kg)	Sources and notes
Straw (15% MC)	13.3	1
Bagasse (50% MC)	7.2	1
Bagasse pellet (10% MC)	15.0	а
Wood pellet (8% MC)	17.5	2
Diesel	42.8	3
HFO	40.5	4
MDO	42.7	5

<u>Sources</u>: [1] Seabra et al. (2010), [2] Visser et al. (2020a), [3] The Engineering Toolbox (n.d.), [4] Giuntoli et al. (2017), [5] Wild (2005). <u>Notes</u>: a. Calculated based on the LHV of bagasse pellets of 0% and 5% MC, respectively 17 and 16 MJ/kg (De Almeida et al., 2017).

Table A4. General cost data.

	Unit	Value	Sources and notes
Diesel price	€/L	0.94	1, a
HFO price	€/tonne	458	2, b
Grid electricity Peru	€/MWh	65.97	3
Labour costs: transport	€/h	4.47	3, c
Labour costs: manufacturing	€/h	4.38	3, c

<u>Sources</u>: [1] World Bank (n.d.), [2] Oilmonster (n.d.), [3] Ministerio de Trabajo y Promocio del Empleo (MTPE), personal communication, 22 July, 2020. <u>Notes</u>: a. Average value of diesel price in Peru for period 2008-2016, b. Average price of HFO (IFO380) in Peru in 2019 (expressed in $€_{2018}$), c. Verified with publicly available average wages in Peru in 2008 (MTPE, 2008).

0	
Process	Value (dry wt%)
Recollection feedstock	0.5
Truck transport	1.0
Pre-treatment	2.0
Deep-sea shipping	2.0
Barge shipping	1.0

Table A5. Weight losses during processes in the supply chain stages (Vera et al., 2019).

Power plant for electricity generation from straw

The techno-economic parameters from Cervi et al. (2019b) for a new power plant, dedicated to generate bioelectricity to supply to the national grid, are provided in Table A6. These parameters are used to determine the LCOE of using straw for local bioelectricity generation.

Table A6.	Techno-economic	parameters for a	a new power	plant (Cervi	i et al 2019b).
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	Linta Nebra						
	Unit	value	Notes				
Reference scale	MW	50	-				
Operating hours	h	8,406	-				
Scale factor	-	0.7	-				
Electrical conversion efficiency	%	25	а				
CAPEX: FCI	Million €	57.61	-				
CAPEX: Working capital	%	5	b				
CAPEX: Grid connection	Million €	8.34	С				
Transmission line	Million €/km	0.30	d				
OPEX	Million €/(MW*y)	0.19	е				
Discount rate	%	12	-				
Project lifetime	y	25	-				

<u>Notes</u>: a. Based on an electrical conversion efficiency range of 20-35% (Cervi et al., 2019b), b. Percentage of FCI, c. Fixed investment for a connection to the national grid, not scale-dependent, d. Costs per km transmission line to an electrical substation, e. Includes consumables, labour, maintenance, overhead and insurance.

Deep-sea shipping

Table A7 presents the data input for deep-sea shipping in addition to data provided in Table 5 in section 3.8.3.

	Unit	Value		Source				
Deep-sea general data								
Density bagasse pellets	kg/m ³	kg/m ³ 650		1				
Stowage factor	tonne/m ³	0.75		2				
Average speed	km/h	20		2				
Capacity factor	%	30		2				
Ballast	%	20		2				
Deep-sea vessel-specific data		Handysize	Supramax					
Deadweight tonnage	tonne	28,000	57,000	2				
Lightweight tonnage	tonne	8,000	13,000	2				
Additional tonnage	tonne	2,000	3,000	2				
Volume limited load	m ³	34,667	72,000	2				
Fuel consumption, full	consumption, full g/(tonne*km)		1.0	2				

Table A7. Input data for deep-sea shipping.

Sources: [1] Vera et al. (2019), [2] Visser et al. (2020b).

Appendix D: Specified values per sugarcane mill and region

Table A8 presents specified values per sugarcane mill, including sugarcane, bagasse and straw production characteristics and measured transport distances. The colours indicate the supply of bagasse from the various sugarcane mills to the same export port within a specific region. The colours correspond to the following regions: green = Piura, blue = La Libertad and orange = Lima. The annally produced sugarcane and bagasse and sugarcane yields are retrieved from MINAGRI (2019). The sugarcane yield represent the average taken from the period 2011-2018. The shipping distance from the export terminals to the import terminal is calculated with a sea route calculator (SeaRoutes, n.d.).

	Unit	Caña Brava	Agro- Aurora	Agr- Olmos	Casa Grande	Cartavio	Laredo	San Jacinto	Para- monga	Anda- huasi
Sugarcane										
Annual processed sugarcane	Mtonne/ y	1.18	1.13	1.03	2.01	1.29	1.49	0.87	1.09	0.43
Sugarcane yield	tonne/ha	143	122	113	150	134	125	135	125	146
Bagasse										
Bagasse production	ktonne/y	345	330	321	626	381	441	257	335	146
Surplus bagasse	ktonne/y	0	0	105	205	124	144	0	0	48
Freed up bagasse: improvements	ktonne/y	17	10	11	21	13	15	13	17	5
Freed up bagasse: straw use	ktonne/y	52	30	32	63	38	45	39	50	15
Straw										
Straw production	ktonne/y	165	159	145	282	180	209	122	152	62
Straw yield	tonne/ha	20.0	17.1	15.78	21.1	18.8	17.4	18.9	17.5	20.4
Sustainable potential: SC70	ktonne/y	69	62	61	123	74	88	55	62	26
Sustainable potential: SC100	ktonne/y	98	89	87	176	105	126	79	88	38
Transport distances										
Field to mill	km	18.8	14.5	8.1	11.3	7.1	17.3	14.6	13.4	10.2
Mill to pellet plant	km	21.6	21.3	0 ^a	35.1	27.9	18.2	0 ^a	53.8	40.9
Pellet plant to export terminal	km	19.9 236.5		26.9 175			132.9			
Export terminal to import terminal	km	10,441		10,870			11,322			

Table A8. Specified values for the sugarcane mills.

Notes: a. Assumed to be zero as an individual pellet plant next to the sugarcane mill is assumed.