CAPCOM-NL

D4: Full Chain Development, Techno Economic Assessment and Life Cycle Analysis

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Contents

1 Introduction

In this work package of CAPCOM-NL project, the full chain development is considered starting from raw material (agricultural crops and residues) and ending at final products (energy, bioethanol or biobased chemicals). The CAPCOM (Clean Agro Pellet COMmodity) is thereby an intermediate product that enables access of small scale biomass providers to large scale end user markets.

Although the idea to produce a commodity will in principle be interesting for all providers of biomass, the project considered three specific sources:

1. Sugarcane residues
2. Palm oil mill residues
3. *Miscanthus*

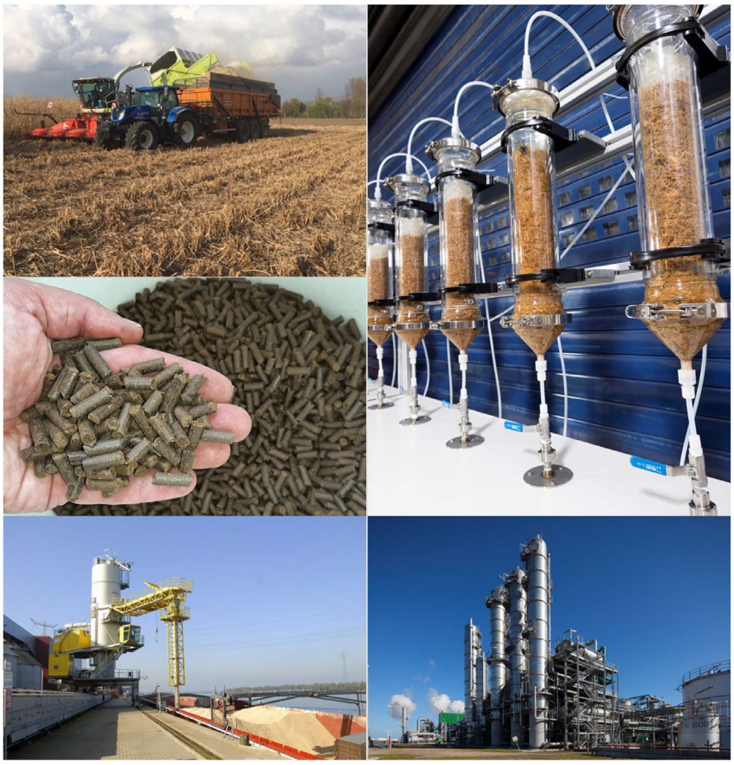
At the same time, three types of end uses are considered:

1. Electricity and heat production
2. Production of bioethanol
3. Production of biobased chemicals

A selection of pathways is then needed in order to make full chain analysis. For this screening is carried out among the different options based on experimental performance and expected feasibility.

For the selected three pathways, process design is carried out which provides mass and energy balances for the production of the CAPCOMs (provided in Deliverable 3). This is used as input for carrying out techno-economic analysis (provided in Deliverable ?) and life cycle analysis (LCA).

In LCA, the overall GHG impacts of three possible chains of CAPCOM are assessed. Cradle to gate impacts (from production of 1 MJ pellet) as well as cradle to grid/wheel impacts are studied considering two end products of energy and bioethanol production from pellets. LCA is a standardized methodological framework for estimating and assessing the environmental impact of a product over life cycle. It consists of four phases: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment and 4) interpretation. In the goal and scope definition the goal of the study is described and the scope is defined which outlines among others the product system, the functional unit, system boundary, allocation method and temporal, geographical and technical coverage. In the inventory analysis, inventory data is compiled of elementary flows (inputs and outputs) related to each unit process within a product system. The data is then expressed per functional unit. The life cycle impact assessment phase of LCA, the inventory data are assigned to the corresponding impact category and then converted into quantitative environmental impacts using characterization factors. Finally, in interpretation phase conclusions and recommendations are drawn and usually involves performing of a sensitivity analysis to test the robustness of the results.



2 Higher value application of CAPCOM's

Higher added value products may improve the profitability of the CAPCOM supply chain. Based on CAPCOM pellets, chemicals could be produced via two ways: biochemically via hydrolysis and fermentation and thermochemically via pyrolysis or gasification. As an alternative, CAPCOM pellets could be used as a raw material for fibre based materials.

2.1 Biochemical pathway

The CAPCOM pellets may be hydrolyzed to produce sugars. After hydrolysis, the produced sugars will be present in a complex mix of water, organics, salts and solids. Purification of sugars from such a mix is quite a challenge. Usually the sugars are fermented to produce a volatile component that may easily be stripped from the broth. Ethanol is a good example of this approach. Alternative fermentations could yield different products (ABE (Acetone, Butanol, Ethanol), Methane, Hydrogen). All these volatile products are small molecules with little functionality and therefore low value.

Fermentation may also yield products with more functional groups such as lactic acid, 1,4-butanediol, amino acids, itaconic acid, 3-hydroxybutyric acid, but these products are less volatile and cannot easily be separated from the broth. Alternative strategies to recover nonvolatile fermentation products include liquid/liquid extraction (organic/water, water/water, reactive extraction, cloud point systems), solvent impregnated resins, adsorption/absorption, membranes (reverse flow diafiltration, electrodialysis, microfiltration), Ion Exchange Chromatography [1-6].

In the fermentation industry it is well known that the costs for purification of the product may be half the total costs. The raw materials may account to max. 30% of the production costs. As cheaper raw materials (from residues) are highly likely to increase purification costs, it is clear that a cut in the raw material costs is easily cancelled by higher purification costs.

2.2 Thermochemical pathway

The thermochemical pathway starts with pyrolysis or gasification. Presence of sodium and potassium reduces the yield of liquid products. Therefore, Clean Agro Pellets are recommended to enhance production of chemicals.

During pyrolysis, the biomass is heated. Biochar and a very complex gaseous stream are produced. This gaseous stream is cooled to produce a liquid phase. The non-condensable part of the gas phase is usually burnt on the spot to provide heat for the pyrolysis process. Depending on the circumstances (temperature, pressure, residence time and presence of catalysts), several interesting chemicals (such as levoglucosan, levoglucosenon, phenols, furans, ketones [7]) may be purified, but a significant part of the mixture will be left over. The leftovers may be (upgraded and) burnt as liquid fuels.

Gasification is performed at higher temperatures than pyrolysis. This leads to further breakdown of the chemical structure of the biomass to mostly C1 and some C2 components. The main advantage of this approach is that the mixture is less complex. The drawback is that only very simple molecules with little functionality remain. Through condensation, BTX (benzene, toluene and xylenes) (10% of energy in raw material) and ethylene (20% of energy in raw material) may be recovered from the gaseous product [8]. Larger molecules with higher functionality may be produced from the CO/H_2 mixture via water gas shift reaction, Fischer-Tropsch process and other pathways. Possible products are: methanol, alkanes and alkenes. Most products lack the presence of two functional groups. Therefore, the value of the products as a chemical is limited. Fischer-Tropsch diesel is regarded as a very high quality diesel or kerosene.

2.3 Composites

Composites are materials made of two or more materials with significantly different physical or chemical properties that when combined produce a material with characteristics different from the individual components. As result, the composite could be stronger, lighter, or less expensive than the traditional materials. Natural fibers owing to their biodegradability, abundance in nature, and low cost, are of high interest to fabricate the fibrous composites without compromising their identities[9, 10]. The CAPCOM pellets, as a compressed form of natural fibers, can be used as raw material for the production of thermoplastic composites. By mixing the CAPCOM pellets with molten plastic in the screws of the compounding machine a homogeneous composite could be produced. In previous experiments performed by Viride, steam-treated and pelleted straw and wood biomass were used to produce composites with up to 30% natural fibers. The dispersion of the natural fibers in the composite was not yet optimal. In pressed films, conglomerates up to 1 mm in size of undispersed natural fiber were observed. Properties were measured and compared to grassy crops, hemp, and flax fibers as an example of commonly used natural fibers. Stiffness, strength, and impact were similar to the fibers from grassy crops and lower than hemp and flax. Elongation at break seemed higher, but more experiments are needed to conclude whether it is a representative advantage[11].

To overcome the undispersed conglomerates and thus improve the properties, a set of steam explosion conditions must be tested. The physical characteristics of the biomass are affected during steam explosions. The higher the severity factor, the higher the disruption of the biomass structure. An optimized severity factor could provide a fibrous material with proper dispersion. The disintegration of the CAPCOM´s prior compounding step could be also considered. However, it has to be evaluated whether an extra process step compensates the economic impact on the complete production process. Compared to common natural fibers, the CAPCOM´s (when scaled up) can be much more cost-effective. Pelleted form of the biomasses at large scale ensures a constant source of raw material, larger quantity, and cost-effective logistics. Also, the more quantity of CAPCOMs can be put into the composite the lower the cost [12]. The percentage of natural fiber in the composite will need to be optimized and experiments must be performed to prove that CAPCOM´s can be added up to a percentage that allows a reduction in cost by at the same time keeping good mechanical and visual properties.

2.4 Discussion

Clearly, the value of chemicals may be considerably higher than the value of liquid or solid fuels. Chemicals with two functional groups have prices around 2000 €/ton. Liquid fuels are around 400 €/ton and solid fuels are around 50-100 €/ton. At this moment considerable subsidies exist for production of electricity and heat. Liquid fuels are promoted by obligations for biofuel blends into transport fuels.

Production of chemicals involves larger investments and therefore higher risks, especially if residues are used as raw material. More and more chemicals are produced from biobased resources (lactic acid, succinic acid, ethylene glycol, thermoset resins, glycerol). But all of these are produced from sugar, starch or vegetable oils, not from residues.

All in all, the production of higher value added chemicals from crop residues may result in profitable processes. But these processes are not running at large scale yet. This is partially caused by subsidies that make low added value applications attractive (heat, electricity and liquid fuels) and partially by the challenging downstream processing of higher added value chemicals especially if residues are used as a substrate. The Avantium process to produce furan dicarboxylic acid (a raw material for production of PEF, an alternative for fossil based PET) seems to be closest to full scale realization.

3 Full Chain Development

3.1 Sugarcane residues

Sugarcane trash is produced as a residue from harvesting of sugarcane. In Brazil, since 2016, pre and post-harvest burning of sugarcane fields is prohibited for land up to a slope of 12%.[1] This change resulted in growing layers of sugarcane trash on the agricultural land. Additionally, in the sugarcane mill sugarcane bagasse is produced as a process residue. The bagasse is used in combined heat and power units to supply the internal heat and energy demands.

Excess bagasse is sold as a fuel or converted to electricity and exported to the grid. There is also potential to make bagasse pellets for export. For this drying, hammer milling and pelletizing are needed to ease transportation. As an alternative, bagasse may be pre-treated with steam and then dried and pelletized. This leads to a denser, easier millable and more hydrophobic pellet.

There are two possibilities to free up additional bagasse for export: one opportunity is to increase the efficiency of the boilers in the sugar mills and the other is cofeeding trash in the mill boilers. Cofeeding sugarcane trash with bagasse for energy generation is of interest as seen in recent literature [13, 14]. RWE sees potential in sugarcane trash to replace bagasse up to 30% in this way. The amount of cane trash that can be cofed with bagasse would be limited due to the higher mineral content of trash. It is therefore considered to extract the sugarcane trash with water to remove minerals. The recovered minerals could be sent to the field as fertilizer. After removal of minerals trash is less likely to cause problems (slagging/fouling) in boilers. Additionally, the sugar cane trash, after extraction of minerals, may follow the same routes as sugarcane bagasse for the production of pellets for export.

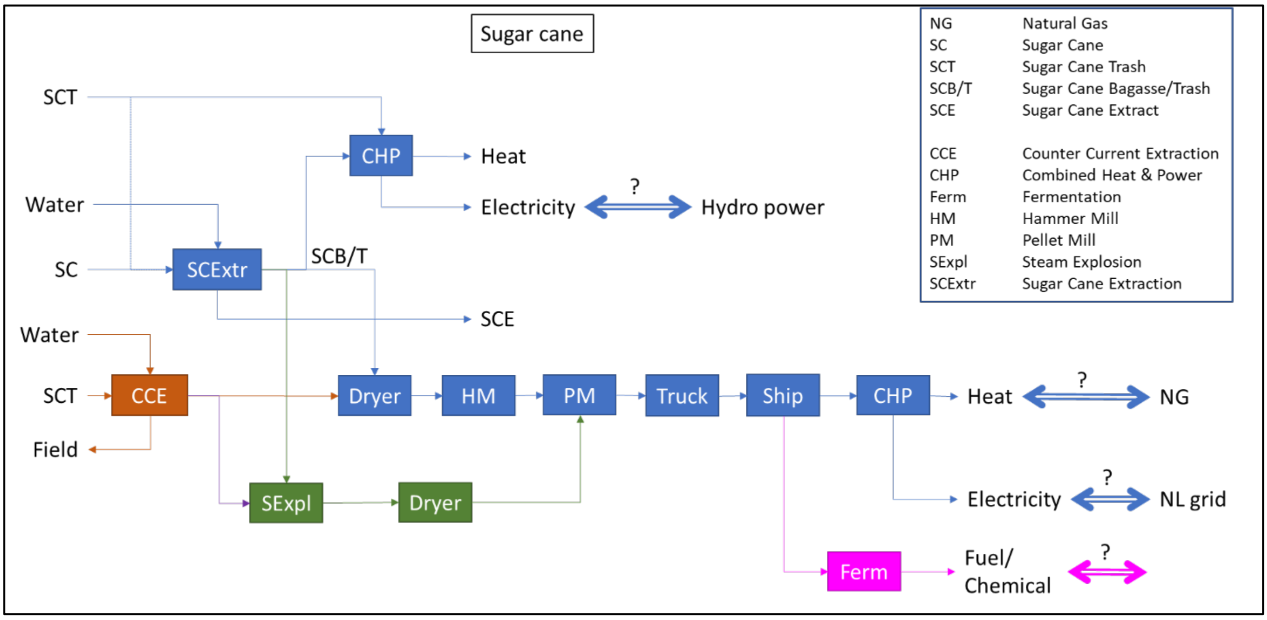


Figure 1 *Sugar cane mill side product upgrading scheme*

3.2 Palm oil mill residues

In the palm oil mill three side products are produced: empty fruit bunch, mesocarp fibre and palm kernel shells. Mesocarp fibre and palm kernel shells are used internally to supply the electricity and heat demand. Excess palm kernel shells may be sold as solid fuel. Empty fruit bunch (EFB) is often returned back to the field or composted. EFB is currently highly underutilized so it is considered as a potential source for biomass pellet for export. EFB is high in minerals that need to be removed

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[1] The São Paulo State Law (n. 11241/2002)

through extraction in order to make it suitable as a fuel. Following drying, hammer milling and pelletizing, pellets are produced suitable for transport. Steam explosion is optional. It can reduce size and increase density and make pelleting and storage cheaper.

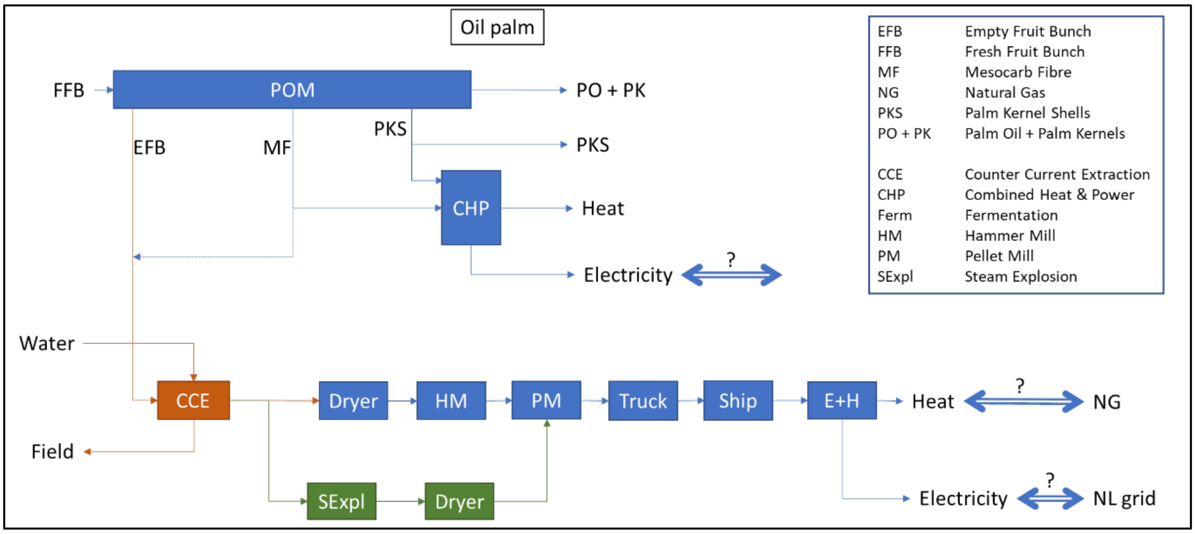

Figure 2 **Palm Oil Mill side product upgrading scheme**

3.3 Miscanthus

Miscanthus is considered as a promising biomass source for pellets due to combination of high yields, low input demand and potential to be grown on marginal land. It improves the soil health and fertility. Since *Miscanthus* is a crop that needs to be grown by a farmer, the price of *Miscanthus* is significantly higher than the price of residues from the palm oil or sugar cane industry. When grown on marginal land, the cost of land will be lower, but the yields will be lower and this will increase the costs of production (ploughing, seeding, harvesting) per kilo harvested.
After chipping and drying, *Miscanthus* is suitable for storage for longer periods. Alternatively, it can be turned into pellets for export. Minerals need to be extracted before pelleting in order to make it suitable as a fuel. Steam explosion is optional.

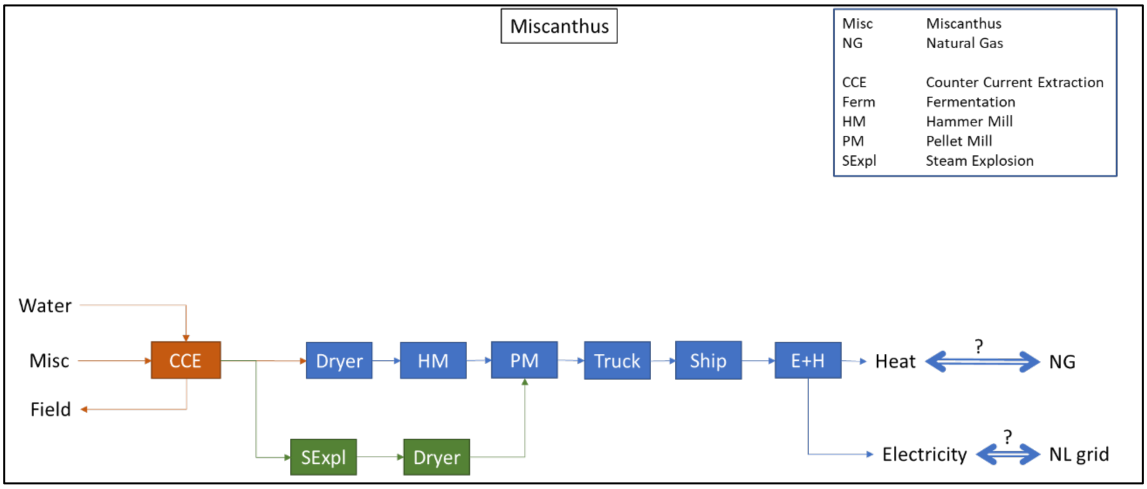

Figure 3 **Miscanthus upgrading scheme**

4 Selection and description of CAPCOM pathways

The budget of the CAPCOM project is limited. Therefore a selection of pathways for full chain analysis needs to be made. For this selection a screening is carried out among the different feedstock and process options presented in Chapter 2. The following criteria were considered:

- Experimental performance during the CAPCOM project
- Expected feasibility in terms of economy, logistics, price and availability

4.1 Selection of pathways

The experiments have shown that more dry matter is washed from the biomass if counter current extraction (CCE) is performed after steam treatment. This will not only lead to loss of material, but is also very likely to cause problems with the treatment of waste water. Toxic components can end up in the washing water, and therefore, the it cannot be used for direct irrigation. Therefore, for the process configuration it was selected to perform steam treatment after CCE.
From sugarcane residues both bagasse and sugarcane trash were considered as potential source for CAPCOM. There is piles of sugarcane trash available on the agricultural land that can be considered to be collected and made into pellets without negative impacts to soil. Pellets made from bagasse, have potential to be an adequate and cost-effective alternative for wood pellets. There are possibilities to free up additional bagasse from sugar mills for this purpose. The sugarcane bagasse is a relatively clean feedstock depleted of minerals, compared with sugarcane trash. This is because the sugar extraction is a washing process itself, further extraction with water is not expected to easily reduce mineral content. Therefore for the production of pellets from bagasse the CCE step can be omitted.
EFB is currently highly underutilized so it is considered as an attractive feedstock for biomass pellet production. It does not find an application other than production of compost. It has no value and the producer can even need to pay to get rid of it. Mesocarp fiber and palm kernel shells on the other hand is already applied as a boiler fuel in most palm oil mills and the excess already has a market as solid fuel. Therefore from palm oil mill residues only EFB is selected as a potential source for CAPCOM.
In the trial experiments, *Miscanthus* proved to be unsuitable for the CCE process. It has a very high water holding capacity and therefore the amount of water needed to wash the biomass is large. *Miscanthus* has channels and they strongly reduce the mass transfer rate. At the same time, *Miscanthus* is a crop that is cultivated and the client must pay for it. In the Netherlands, the *Miscanthus* prices are almost equal to the price of white wood pellets. Therefore, there is no margin for the production of pellets from *Miscanthus*. Therefore, this feedstock is not selected as suitable for CAPCOM.

Based on the criteria and considerations as described above, 3 pathways to produce CAPCOM were selected:

1. Sugarcane bagasse -> CAPCOM
2. Sugarcane trash -> CAPCOM
3. Empty fruit bunch -> CAPCOM

Also 2 end uses of CAPCOM’s are considered for analysis of full chain analysis according to the project plan:

1. CAPCOM -> Electricity
2. CAPCOM -> Ethanol

4.2 Process setup

Figure 4 shows the resulting process flow diagram for the production of CAPCOM pellets. The following processes are involved:

1) Size reduction: A shredder to reduce the biomass raw material to the required size to the counter current simulated moving bed (CC SMB) extraction;
2) Current simulated moving bed (CC SMB) extraction: The CC SMB extraction leaches out the minerals from the biomass raw material (mainly K and Cl);
3) Screw press: A screw press is needed to remove mechanically the maximum possible quantity of water (dewatering) from the biomass solids after the CC SMB. This is done to avoid large energy demands for the thermal drying;
4) Pre-dryer: A thermal dryer is needed to tune the moisture of the washed biomass to the required moisture content of the steam explosion (SE) process;
5) Steam explosion (SE): SE reactor upgrades the biomass into a higher energy content commodity material;
6) Post-dryer: A post dryer is needed to reduce the moisture to the requirements of the pellets press;
7) Pellet press: A pellet press unit provides the pellets and thereby increases the energy density of the upgraded biomass suitable for transport.

As described above the CC SMB and screw press steps can be omitted for bagasse. It is considered that this pellet production will be situated at the sugar mill for sugarcane trash and sugarcane bagasse and at the palm oil mill for EFB. In this way, the energy needs can be integrated with the mills. Because sugarcane trash is left on the field it needs to also be collected and transported to the sugarcane mill. Bagasse and EFB are attained as process residues and already located at the mill. The produced pellets at the mill then need to be transported to the harbour by truck and then to the port of Netherlands by transoceanic transportation. Both electricity and ethanol production from CAPCOM pellets are considered to take place in the vicinity of the port of Rotterdam.

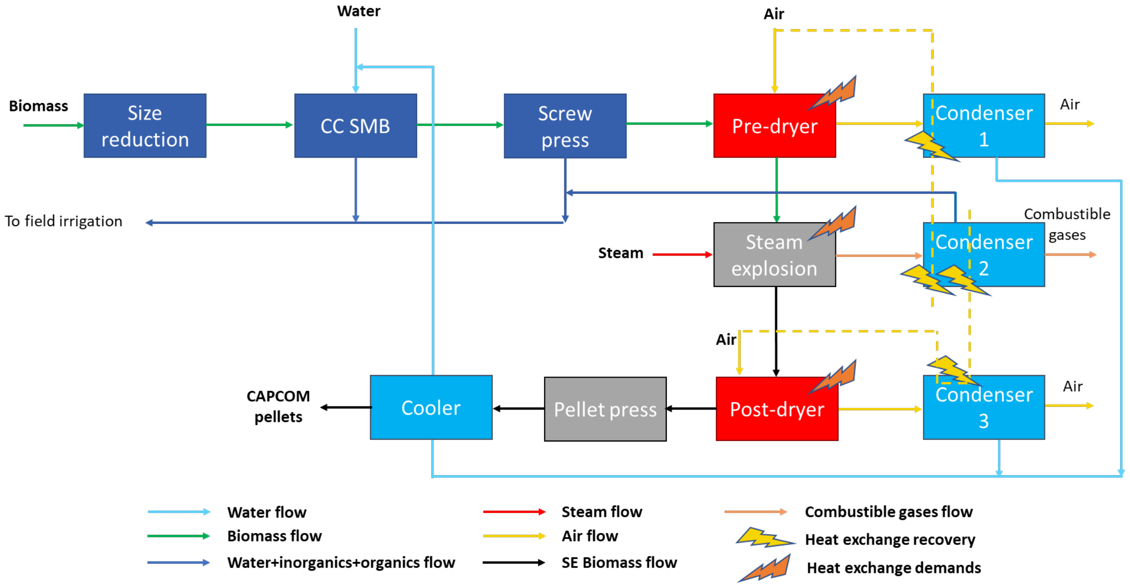

Figure 4 ***Process flow diagram for the production of CAPCOM pellets***

5 Technical and economical evaluation

5.1 Structure of the evaluation

This report is about three raw materials which could be converted by a process of washing and steam explosion into biomass pellets for the Dutch (or European) market. The selected raw materials are sugar cane bagasse (SCB), sugar cane trash (SCT) and empty fruit bunches from palm oil production (EFB). In this technical and economical evaluation or assessment (TEA) the main focus is on what would be the production costs to deliver it to the Dutch market, including logistics. For this calculation is this assumed that the sugar cane products are produced in Brazil and the EFB in Colombia.
Other parts of this report discuss the technical possibilities, the product properties and the environmental effects in a life cycle analysis (LCA). For this TEA energy use, mass balances and compositions are taken from, or calculated with, data of the experiments. The TEA is also in line with the assumptions for the life cycle analysis. Information on costs is mainly taken from literature and converted to the capacities used here.
The investment costs are an important issue. For the TEA a commercial size of the installation is chosen, which capacity is related to actual plant capacities in the sugar cane or palm oil producing countries [15, 16]. For sugar cane it is assumed that there might be two separate lines to meet the full capacity of the cane sugar plant. The EFB has to be shredded and chopped before the salts can be washed out. Sugar cane trash has only to be chopped before washing and bagasse is already washed and can go directly to the steam explosion reactor. So between the different processes there is not only a difference in size, but also a difference in number of process steps. Based on equipment prices and multiplying factors total investment costs are calculated.
Yearly capital costs can be derived from the investment costs. Adding of the different variable costs factors count up to the production costs. The price of the biomass source is an important cost factor. Special attention is given to the energy costs because it appeared to be an important cost factor. Also special attention will be given to the fertilizer role, if the wash water is brought back to the fields.
Finally the costs for transport of the pellets to a location nearby Rotterdam Harbour are calculated.

5.2 Investment costs

5.2.1 General assumption about the biomass to pellets plants

The size of the biomass to pellets installation is related to the plant capacity in the sugar cane or palm oil industry. For pellets from EFB an input capacity of 9 ton[2] dry mass EFB per hour is assumed. This in line with a normal capacity of a palm oil mill. For the SCB and the SCT dry mass input capacities of 20 ton/hour are assumed. Because sugar cane factories are substantial larger than oil mills this can even result in two separate production lines per product per location.
For cane sugar production the number of operating hours depend on the possibility to harvest sugar cane. When there is a lot of rain, harvesting stops. You can’t store sugar cane stalks because the sugar will immediately start fermenting[3]. In the economic evaluation 6000 full load hours are assumed. A bit more than the 5000 full load hours for the palm oil production.

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[2] In this report 1 ton is equal to a metric ton or tonne.

[3] Harvesting time in Colombia and Costa Rica, 4000 h, in North East Brazil 5000 h. Bagasse can be stored and pelletized after one month of stabilization reaching 6000 operating hours/y.

Table 1 Input parameters for TEA

	SCT (trash)	EFB	SCB (Bagasse)
Dry biomass input (ton/h)	20	9	20
Dry biomass input (ton/y)	120000	45000	120000
Wet biomass input (ton/h)	23.5	20	40
Pellet output (ton/h)	16.8	7.8	20.0
Number of operating hours	6000	5000	6000
Pellet output; 15% moisture (ton/y)	100800	39200	120000

Sugar cane trash (SCT) has a low water content, when it comes from the field. It has to be reduced in size and washed to reduce the amount of salts. After pressing and pre-drying it is ready for the steam explosion reactor. The empty fruit bunches (EFB) of palm oil have a larger size than the trash and need additional size reduction for instance in two steps (shredding and chopping). Sugar cane bagasse (SCB) has already passes several processing steps to reduce the size, remove the sugar (including the salts) and a lot of the water. So it is directly ready for the steam explosion reactor. After the steam explosion, the products are dried and pelletized. The produced pellets have a moisture content of about 10%.

5.2.2 Method for the calculation of the total capital requirement

At TNO a calculation sheet is used for calculation of the investment costs, based on the bare equipment costs. This model is based on a method recommended by the American Association of Cost Engineers (AACE) [17]. The model uses a lot of multiplying factors. The factor which are used in this costs calculation are explained here. By using the AACE method, certain costs are prevented from being forgotten or skipped. For the method itself, reference is made here to the AACE publication [18].

Total process capital and process contingency costs (technical)
For the shredder and the chopper installation a setting labor factor is used of 30% of the bare equipment costs. Bare equipment costs are based on Alibaba[4] data [19, 20] and were compared with other sources. Installation costs[5] are equivalent to the AACE standards for "Crushing, grinding and conveying". This includes the necessary materials and labor. Indirect labor costs are set in 115% of direct labor for installation. This resulted in total process capital factor of 3.4 of the bare equipment costs. Finally a low process contingency is added of 5% of the total process capital because this part of the process is seen as used commercially.

For the Counter Current Simulated Moving Bed (CCS MB), the screw press and the pre-dryer a setting labor factor is used of 20% of the bare equipment costs. Installation costs are equivalent to the AACE standards for "Solids handling < 204 °C". Indirect labor costs are set in 115% of direct labor for installation. This resulted in total process capital factor of 3.1 of the bare equipment costs. Bare equipment costs were calculated back with those factors from literature [21, 22]. Finally a process contingency is added of 13% of the total process capital, normally used if "Full-size modules have been operated (range 5-20%)".

For the steam explosion reactor a setting labor factor is used of 20% of the bare equipment costs. Installation costs are equivalent to the AACE standards for "Solids-Gas < 204 °C, <10.4 bar". Indirect labor costs are set in 115% of direct labor for installation. This resulted in total process capital factor of 2.9 of the bare equipment costs. Finally a process contingency is added of 13% of the total process capital, normally used if "Full-size modules have been operated (range 5-20%)". Cost data are derived, among other publications, from Wolbers (2018) [23].

For the pelletizing the same factors are used as for the CCE MB. Cost data are derived, among other publications, from Wolbers (2018) and Hoque (2006) [23, 24].

For the heat exchangers (condensers) used in the heat integration a setting labor factor is used of 20% is used of the bare equipment costs, calculated with Latten and Nijssen (2003) [25]. Installation costs factor are taken from the AACE standard for "gas <204 °C and <10.3 bar". Indirect labor costs

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[4] https://www.alibaba.com/showroom/biomass-shredder-price.html

[5] Installation costs includes foundations, structures, buildings, insulation, instrumentation, electrical, piping, painting and miscellaneous.

are set in 115% of direct labor for installation. This resulted in total process capital factor of 3.1 of the bare equipment costs. Finally a low process contingency is added of 5% of the total process capital because this part of the process is seen as used commercially.

Bare equipment costs

The bare equipment costs are in most cases taken from other studies and with a scale factor of 0.7 recalculated to the size in this report. Sometimes also a water content correction has been used. Data in dollar or another currency are first transferred to euro of the same year and after this converted to euro's 2019 with Dutch inflation figures[6]. If the literature mentioned installed costs or total process capital this is recalculated into a theoretical figure for bare equipment costs. In this way the different installation parts could be compared, see Table 2. For the condensers and the cyclone separate calculation were made base on the needed heat transfer area and the gas volume. Although the construction cost might be lower in Brazil and Columbia [26], this is not taken into account because there are no good figures to calculate this for this type of installations in rural locations.

Table 2 Bare equipment costs (indicative)

In 1000 €	SCT (trash)	EFB	SCB (Bagasse)
Shredder	0	33	0
Chopper	69	40	0
Counter Current Extraction	78	46	0
Screw Press	27	17	0
Pre-dryer	120	44	0
Condenser 1	124	62	0
Steam explosion reactor	314	184	354
Condenser 2	102	68	99
Post dryer	285	167	322
Cyclone	17	10	19
Pelletiser	405	238	457
Condenser 3	93	56	99
Pellet cooler	36	21	40
Total	1670	986	1390

In Figure 5 the several parts have been added together to give a clearer picture. Bare equipment costs of the EFB pellet plant is lower, because it had a much lower capacity. Comparing the trash and bagasse case makes directly clear that about ¼ of the investment costs are related to size reduction and washing.

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[6] https://opendata.cbs.nl/#/CBS/nl/dataset/70936ned/table

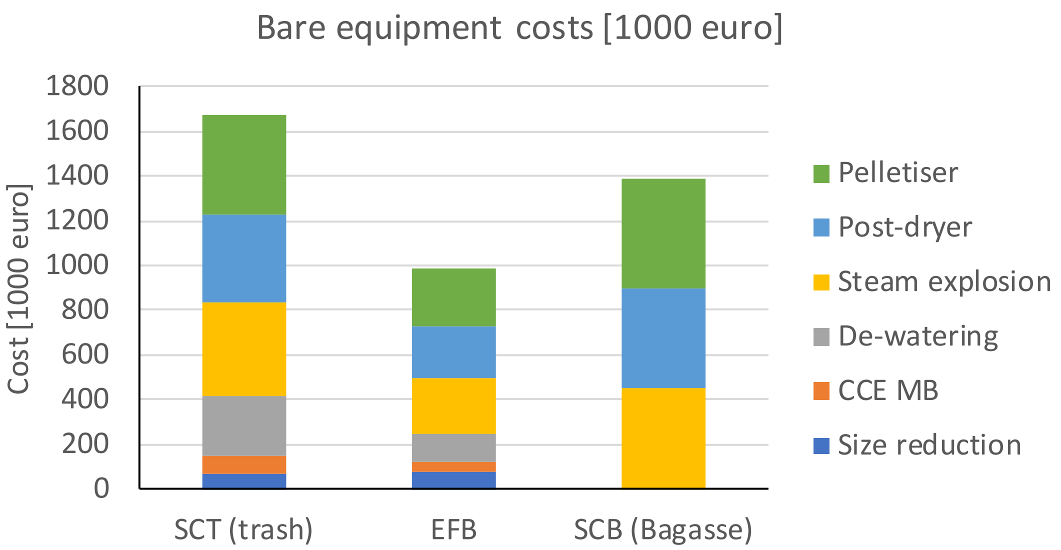

Figure 5 ***Bare equipment costs of pellets from three types of biomass feedstocks***

From the experiments it appeared that the pre-dryer step is probably not needed in the EFB case. Without the pre-dryer and the condenser 1, bare equipment costs go down with 11%. If this route is fully calculated, it appeared that pellet production en transport costs for EFB go down with 5%, see the variant in Table 13 sensitivity analysis.

Total plant costs (technical)
After calculating the direct and indirect field costs (together the “total process capital; TPC”), some additional costs can be added. General facilities is set at 5% of the TPC, this is lower than the normal figure of 15% because a lot of facilities will be already in place. The “home office, overhead and Fee” is set on 10% of the TPC (this includes for instance the cost for the design, engineering and coordination by the contractor). The total plant costs include also the process contingency costs. There are no costs added for project contingencies[7].
Finally there are start-up and first operating costs: Start-up costs are mainly estimated as the operation costs and energy costs of one month. As working capital also 2 months of operating costs are added. Startup costs and working capital are not seen as a part of the depreciable investment. This is why this is not always taken into account in economic assessments.

Total investment costs
Table 3 shows the resulting cost figures of the several cumulative parts. As can be seen, the amount of capital related to the buying of the main equipment is much lower than the amount of capital to build the plant and starting to operate it. In general investment costs and operating costs are used to calculate the return on investment, to see how attractive an investment is. For such a calculation the selling prices of the products are needed and a lot of other assumptions are needed like taxes, depreciation[8], building time and cost increases. Here a simpler method is used. An annuity is calculated based on a lifetime of 15[9] years and a mixed financing with return on own capital of 12% (so there is a profit for the investor) and an interest of 2% on a loan. This resulted in a fictive interest of 5%[10] and an annuity of 0.0963[11]. In this way is easy to see what the role of the investments is in the production costs of the pellets. It is also an easy way to make calculations without other assumptions. Total capital requirements are multiplied with the annuity to get the yearly costs of the investment.

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[7] Project contingencies could be as high as 30% of the TPC. (or 25% of TPC+ process contingencies + “Home office, overhead and fee”.

[8] Colombia has a high inflation rate. This makes it complicated to make such a calculation in the Colombian pesos.

[9] This is a mix of the depreciation for installations (~10 years) and buildings and infrastructure (~25 years).

[10] An own capital (equity) share of 30% and a loan share of 70% results in a fictive interest of 5%.

[11] The annuity indicates which constant costs you have to use annually over the lifetime to pay interest and full repayment.

Table 3 ***Structure of investment costs and the effect on production costs***

In 1000 €	SCT (trash)	EFB	SCB (Bagasse)
Bare equipment costs (k€)	1668	986	1391
Total process capital (k€)	5121	3034	4203
Total plant costs (k€)	6344	3750	5203
Total capital requirements (k€)	7752	4246	6600
Annuity	0.0963	0.0963	0.0963
Yearly cost of investment (k€)	747	409	636
Investment effect on pellets costs (€/ton)	**7.4**	**10.4**	**5.3**

In Table 3 the effect of the smaller size of the EFB pellet plant can be seen, although the plant is cheaper in total investment per produced ton of pellets, the costs are higher. It also shows that the investments for bagasse are lower than for trash because shredding, washing and pre-drying are not needed.

5.3 Operating costs (OPEX)

5.3.1 Operating costs (excluding utilities and materials)

For the operating costs also the AACE method is used. The resulting costs can be seen in Table 4.

Table 4 ***Operating costs (excluding utilities and materials)***

In 1000 €	SCT (trash)	EFB	SCB (Bagasse)
Total direct and indirect labour	842	399	513
Payroll Overhead	210	100	128
Maintenance Material Costs	127	75	104
Indirect Material Costs	81	38	49
Property Taxes and Insurance	127	75	104
Administration and Corporate	210	100	128
Sales Expense	81	31	96
Yearly operating cost (ex. utilities and materials)	1678	819	1123
Effect operating costs on pellets costs (€/ton)	**16.7**	**20.9**	**9.4**

As can be seen, about 50% of the operating costs are directly related to direct and indirect labour. For the SCT case it is assumed that 14.4 operators are needed earning 30000 euro/y (432 k€) and for the SCB case, with less process steps only 8. For EFB, with less operating hours only 12 operators are assumed earning 16000 euro/y. The wages in Colombia are lower than in Brazil [27, 28]. The labour costs doubles due to direct supervision, maintenance labour and indirect labour. Although most multiplying factors are set on a lower level than the (old) AACE baseline value, operating costs have a substantial effect on the production costs for pellets.

5.3.2 Operating costs: utilities and materials

Biomass feedstock

IF a price is put of the biomass feedstock, this has substantial effects on the overall cost picture. The price on dry basis of the biomass input comes with an increase for losses directly back in the production costs for the pellets.

In the EFB case it could be assumed that EFB had a negative price. The EFB is already at the location of the plant and to transport it back to another location, will cost money. But if EFB is brought back to the plantation it has a value for its organics and minerals content. Several studies mentions EFB prices or values around 4 €/ton wet or 9 €/ton dry [29, 30].

Also bagasse is already on the location of the plant. But a part of the bagasse is already used as a fuel for the boilers. The surplus can be sold as fuel, so it has a commercial value. If bagasse is used at the plant location there is no need for additional store, preparing for transport and truck transport. So the internal price is lower than the commercial value. Literature gives no clear value, prices vary between

0 €/ton (internal) and 15 €/ton (sold) for bagasse on wet basis with 50% moisture. Sometimes the value is related to the electricity price, for electricity which good be produced with bagasse, a steam boiler and a back pressure turbine [31, 32]. In the calculation in Table 5 a value of 30 €/ton on dry basis is used.

For years trash was burned in the fields causing a lot of air pollution. In Brazil this is no longer allowed, but it is such a great amount that is has negative effects on the sugar cane yields if it is left on the fields. Although, by not removing, it adds to the retention of fertilizers and minerals. It is possible to collect it a part of it and use it as a fuel partly substituting bagasse in the sugar mill boilers. So it is a product with a negative price in the fields, but value increases if it is transported to the sugar mill. The transportation costs are a substantial factor in the trach price. In the calculation it is assumed that is has a value of 13 €/ton on wet basis and 15 €/ton on dry basis when it arrives at the sugar mill location [31, 33]. Off course, it is possible to make calculations with other biomass prices. It is relatively easy to put in other values in Table 5 and calculate the effect on the pellet costs. The feedstock value is on dry basis, the pellet costs are for pellets with 15% moisture.

Table 5 Relation between biomass feedstock value and pellet costs

	SCT (trash)	EFB	SCB (Bagasse)
Value of biomass input (€/ton on dry basis)	15	9	30
Multiplying factor related to input-output	1.190	1.148	1.000
Effect feedstock value on pellets costs (€/ton)	**17.8**	**10.3**	**30**

Fertilizer value

With the EFB and the trash also "fertilizer" value is removed from the fields [34]. By washing the feedstocks a substantial part of the fertilizer value (89-96%) ends up in the wash water. When this water is returned to the fields, and minerals and fertilizers are recycled, this generates value, because less fertilizer have to be bought. The value is mainly in K, a lesser amount in Mg and a small amount in P. It is possible to lower the biomass feedstock price with the recycled value, but here the value is made explicit. Because bagasse is already washed out in the sugar production the additional process steps does not lead to waste water with a significant amount of fertilizer ort minerals. The quantities are calculated here from masa balances of the incoming and outgoing solid biomass from the experiments. This is multiplied by the price of fertilizer muriate of potash (K), kieserite (Mg), rock phosphate (P) taking into account the content of K, Mg and P [35]. Because kieserite also contains sulfur (S), no additional value is given to sulfur recycling. The results can be found in Table 6.

Table 6 Fertilizer value of wash water brought back to the plantation

€/ton wets	SCT (trash)	EFB	SCB (Bagasse)
€/ton on wet basis	4 (range 3-6)	7.2 (range 4-12)	-
€/ton on dry basis	4.7 (range 3.5-7)	15 (range 9-26)	-

There is not much literature on the value of EFB and Trash in relation with fertilizers. The value of trash is in range with other publications. For EFB two old publications mentions values at the lower end of the range.

Energy prices

A substantial amount of energy is needed for heating, drying and the steam explosion. This amount is already reduced by the of heat exchangers and the use of condensing energy from evaporated water during drying. Also the press for dewatering and the pellet press demand a non-negligible amount of electricity. Buying the electricity from the grid can substantial increase the production costs.
In case of a palm oil mill, the waste water, palm oil mill effluent or POME, can easily be digested producing biogas [36]. This biogas can be used in gas engines to produce electricity, and if needed, steam. There are also solid waste stream like fibers and shells which could be used for steam production, and if needed, with a steam turbine for electricity production. Shells can also be sold as a biomass based fuel.
The sugar cane mills, produce bagasse, the residual product after washing of the sugar from the sugar cane stalks. This bagasse is used as fuel for steam boilers in the factory, but also sold as a biomass

based fuel. To be able to sell more bagasse a part of the boiler input might be substituted by trash. In the factory steam turbines are used to produce electricity.

Table 7 shows the prices of steam produced with own fuels [16, 31, 36]. Those prices will be used in the TEA. Also electricity is assumed to be produced locally. The price is related to what this electricity would yield, if it was sold [13]. This are yearly mean market prices for Brazil and Columbia. For comparison also the electricity prices are shown if this should be purchased on the national market.

Table 7 Prices for steam and electricity

	Steam (from own biofuels)	Electricity (selling own production)	Electricity (bought from the grid)
Brazil	2.5 €/GJ	13.6 €/GJ (49 €/MWh)	30 €/GJ (108 €/MWh)
Colombia	2.7 €/GJ	9.4 €/GJ (34 €/MWh)	30 €/GJ (108 €/MWh)

Note: If the condensate of the steam is not reused, steam costs might raise with ~ 0,54 €/GJ.

Other utilities and materials

Water for washing the products is set on a lower price of 0.2 euro/m^3. Locally available surface, rain or ground water can be used for this. It is assumed that in case of Trash and EFB condensation water and relatively clean waste water is reused in the washing step of the feedstocks.

Most of the water in the steam cycle will be brought back to the steam boilers to be reused. But a part of the steam is used for the steam explosion reactor. This condensate is not recycled. To this steam an additional cost is added of around 1.5 €/m^3 for make-up water or (1.5/2.8 GJ/ton steam=~) 0.54 €/GJ steam. About 2/3 of this price is related to buying of drinking quality water (or cleaning water at the location); 1/3 of the prices is related to converting this into boiler feedwater. The drinking water price depends on location and can depend on the time of the year. In Brazil this price can also be combined with the costs for waste water cleaning, which makes it difficult to find a good value [37]. Also literature prices for boiler feedwater preparation have a large range.

The steam explosion reactor produces also a small amount of biogas with a low heating value. This gas can be used or sold and the value is set on 0.75 €/GJ. The waste water has to be stored and brought back to the plantation for conserving the valuable compounds and for irrigation purposes. For this a cost factor of 0.1 €/m^3 is put on the waste water. No additional profit is added for the possibility of biogas production from this waste water. Is should be mentioned that is the waste water is not recycled, waste water treatment might costs 1 €/m^3. The total of the operating costs for utilities and materials can be seen in Table 8.

Table 8 Operating costs (utilities and materials)

In 1000 €	SCT (trash)	EFB	SCB (Bagasse)
Biomass feedstock price (dry basis)	*Trash 15 €/ton*	*EFB 9 €/ton*	*Bagasse 30 €/ton*
Biomass feedstock costs in k€	1800	405	3600
Electricity price	*0.049 €/kWh* *13.6 €/GJ*	*0.034 €/kWh* *9.4 €/GJ*	*0.049 €/kWh* *13.6 €/GJ*
Electricity costs in k€	1286	491	973
High Pressure (HP) steam price	*6.44 €/ton* *2.3 €/GJ*	*7.56 €/ton* *2.7 €/GJ*	*6.44 €/ton* *2.3 €/GJ*
HP steam costs in k€	1027	362	793
Boiler feed water for steam explosion costs (1.5 €/m^3)	62	24	74
Process water (0.2 €/m^3)	72	20	0
Biogas profit (0,75 €/GJ HHV)	-42	-16	-49
Waste water (0.1 €/m^3)	40	16	6
Yearly operating cost (utilities and materials)	4245	1302	5397
Effect utilities & materials on pellets costs (€/ton)	42.1	33.2	45.0

5.4 Transport

Once produced the pellets must be stored and transported to the consumer. In this case first from the production location to the harbour, then overseas to Europe (Rotterdam) and then from the harbour to a power plant located 50 km sailing inland. Another "partly comparable" product that is exported from Brazil to Europe is soybeans. In land and overseas transport costs for soybeans are published regular by the USA (Brazil Soybean Transportation) [38]. From the 2020 information a simple calculation method has been derived consisting of a fixed amount (for available of the vehicle, waiting time, etc.) and a flexible amount per kilometer. Data are calculated from transport distances of > 300 km (and >5000 km for sea transport). It is assumed that harbour coast are included in the sea transport costs and that any empty driving back is included in the costs. The calculated values can be found in Table 9. For the 50 km sailing inland in the Netherlands costs are estimated at 1.25 €/ton, based on more frequently transport.

Table 9 ***Cost functions for soybean transport in Brazil including long distance sea transport***

Means of transport	Cost factor	Cost factor	EFB
Inland shipping	fixed	9.5	Euro/ton
	distance dependent	0.009	Euro/ton.km
Rail	fixed	13.2	Euro/ton
	distance dependent	0.009	Euro/ton.km
Truck	fixed	3.9	Euro/ton
	distance dependent	0.042	Euro/ton.km
Sea transport (incl. harbour)	fixed	16.4	Euro/ton
	distance dependent	0.0005	Euro/ton.km

For Brazil a domestic transport distance by truck of 400 km inland transport is assumed. The Brazilian data are also used for Colombia. For Colombia a rail transport distance of 100 km is assumed. To get the pellets to the station and for transshipment an additional 10 km per truck is added. Distance to Rotterdam from Brazil is 10049 km and from Colombia 8470 km. The resulting transport costs can be found in Table 10. As variant in the table also costs are given if sea transport is comparable with coal[12].

Table 10 ***Transport costs to power plant near Rotterdam***

In €/ton	SCT (trash)	EFB	SCB (Bagasse)
Road (transhipment)		4.3	
Rail	20.5	14.1	20.5
Sea transport	21.4	20.7	21.4
Inland Shipping NL	1.25	1.25	1.25
Total	43.2	40.4	43.2
Total (low) based on coal transport sea shipping	32.1	30.1	32.1

If in the Brazilian case the 400 km domestic transport is not done by rail, costs are about the same. If done by inland shipping total transport costs might be 8% lower. But inland shipping must then be possible and travel distance to get from production location to the harbour must not be too much longer. If travel distance raise to 800 km and this is all done by truck total transport costs raise to costs 43.9 to 59.8 €/ton (36%). By rail it is 8% for 800 km and by inland ship it is only 3%. So for a location more land inwards it is better to use a cheaper and more energy efficient means of goods transport than trucks.

This TEA has not investigated or optimized what the best storage method would be. This depends on the number of producers and pellet volume and the port facilities in the country of origin and in Rotterdam. Also the capacity per sea ship capacity is important in such an optimization. An IEA rapport of 2019 gives details for pellet transport from Brazil to Europe [39, 40]. If the lowest

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[12] https://www.hellenicshippingnews.com/coal-freight-rates-face-20-40-hike-from-2020-woodmac/

mentioned values and the higher are count the maximum range is 26-102 €/ton. So the calculated transport costs here are at the lower end of the range. The calculated costs fits better with regular transport and large volumes.

5.5 Total picture

5.5.1 Costs per ton or GJ pellets

The various components of the production and transport costs are brought together in Table 11. Transport is from a location not too far from the coast in Brazil or Colombia to a power plant near Rotterdam Harbour in the Netherlands. The data of the table can also be seen in Figure 6. The fertilizer value gives negative production costs, so the yellow segment must be deducted from the total.

Table 11 ***Production and transport costs of pellets from three types of biomass feedstocks***

Euro/ton	SCT (trash) Brazil	EFB Colombia	SCB (Bagasse) Brazil
Capital costs	7	10	5
Operating costs	17	21	9
Biomass feedstock[13]	18	10	30
Fertilizer value	-6	-17	0
Electricity	13	13	8
Steam	10	9	7
Other	1	1	0
Subtotal	61	47	60
Transport to NL[13]	43	40	43
Total	104	88	103

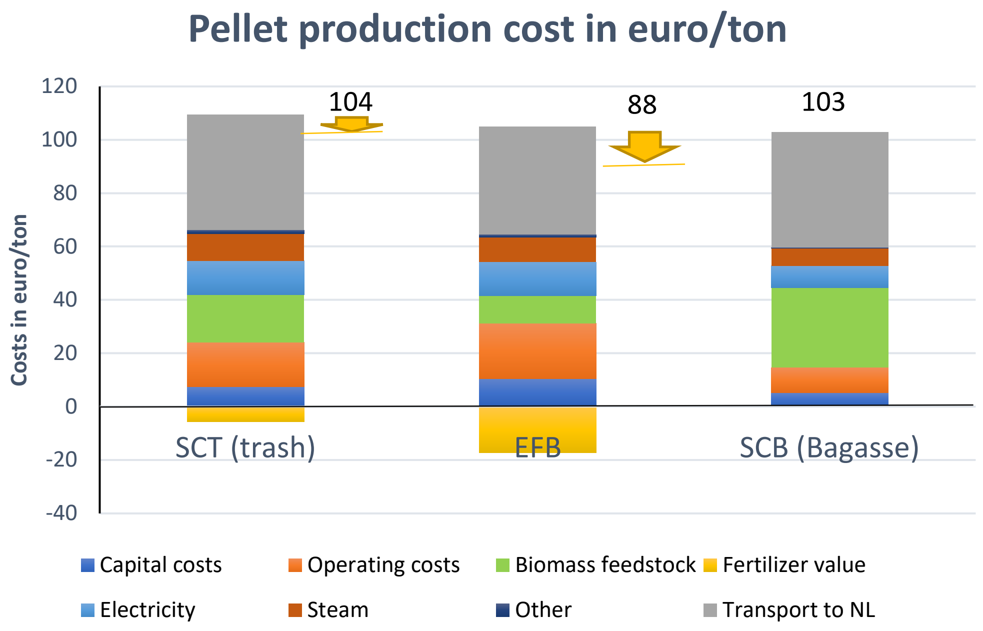

Figure 6 ***Production and transport costs of pellets from three types of biomass feedstocks***

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[13] Real life cost will probably be higher, see the sensitivity analysis.

For comparison: the current price for wood pellets is around 120 €/ton[14]. The production and transport costs have been converted in €/GJ (LHV) in Table 12. Costs related to the HHV are ~7% lower[15]. This is also shown in Figure 7. The effect of the fertilizer value is indicated by arrows in this figure. It should be mentioned that these figures are the outcome of the analysis. Real life cost for instance for transport of the feedstock value can be higher.

Table 12 Production & transport costs of pellets from three biomass sources in €/GJ

Euro/GJ	SCT (trash) Brazil	EFB Colombia	SCB (Bagasse) Brazil
Capital costs	0.45	0.61	0.31
Operating costs	1.01	1.22	0.54
Biomass feedstock	1.08	0.61	1.75
Fertilizer value	-0.34	-1.01	0.00
Electricity	0.77	0.73	0.47
Steam	0.62	0.54	0.38
Other	0.08	0.07	0.02
Subtotal	3.67	2.77	3.47
Transport to NL	2.62	2.37	2.51
Total	6.29	5.14	5.98

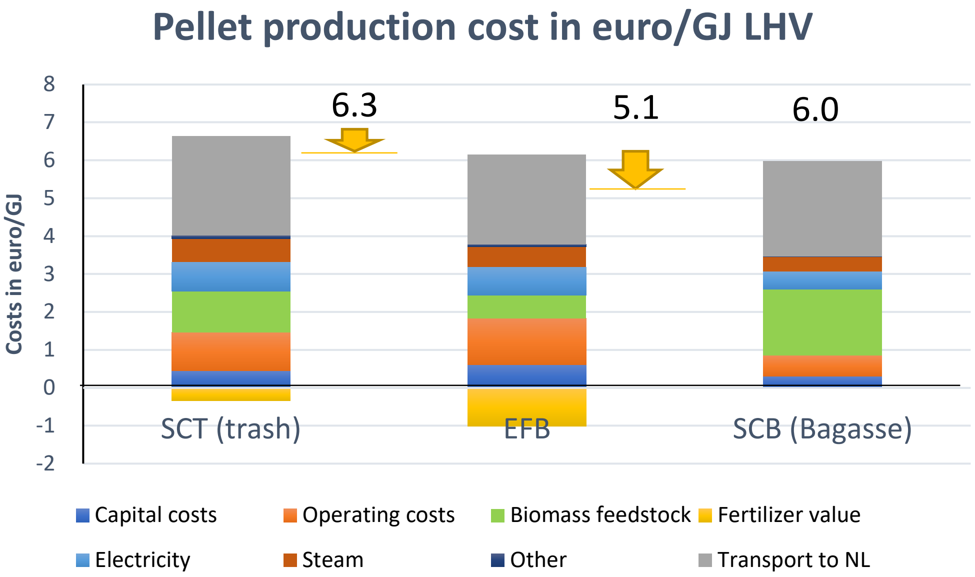

Figure 7 Production & transport costs of pellets from three biomass sources in €/GJ

Pellets competing with coal use

In the project there are several applications for the pellets including use for co-firing (or 100% biomass firing) in a coal power plant or use for ethanol production. Recently it appeared the pellet price is competing with coal. The mean coal price in the Netherland (April 2020-April 2021) is around 65$/ton[16] or 55 €/ton. With a combustion value of 26.5 GJ/ton (LHV) this is equal with 2.1 €/GJ. For burning coal in a power plant in the EU emission trading system (EU-ETS). also CO_2 emission rights have to be bought. In 2019 and 2020 the mean prices[17] were around 25 €/ton CO_{2eq}. In the second half of 2020 prices begin to rise and this trend accelerated in the beginning of 2021 with a mean price of 42.55 €/ton on 31 March 2021 (in April 2021 prices went up further). If a CO_2 emission factor of 94.6 ton CO_2/GJ coal is used. 42.55 €/ton is equivalent with 4 €/GJ coal. With a range of 5.1 to 6.3 €/GJ for pellets (4.8 to 5.9 on HHV basis) they are fully competing with a coal price (including the CO_2

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[14] https://www.eex.com/en/market-data/biomass
[15] https://phyllis.nl/
[16] https://www.energiemarktinformatie.nl/
[17] https://www.investing.com/commodities/carbon-emissions-historical-data

price) of 6.1 €/GJ[18]. It should be mentioned that those cost values include uncertainty ranges and can change in future.

5.5.2 Sensitivity analysis

The effect of several variant on the inputs can be seen in In Table 13. First the effect of a higher annuity is calculated. An annuity of 0.1437 results from 40% own capital with 15 return on investment (was 30% with 12%) 60% loan with 2% interest (was 70% with 2%) and a lifetime or 10 years (was 15 years). It appears that this has only small effects on the production cost from trash and bagasse and some effect by EFB.

In the second variant the price or value of the feedstock is raised with 10 €/ton (dry mass). This has substantial effects on all the three routes. Also substantial effect has the use of grid electricity instead of using own produced electricity. Only the effect for bagasse is lower because there is no washing step needed and there is no electricity needed for a screw press.

Table 13 Sensitivity analysis

Euro/GJ	SCT (trash) Brazil	EFB Colombia	SCB (Bagasse) Brazil
Current outcome	6.29	5.14	5.98
Higher return on investment; higher annuity	0.0963->0.1437	0.0963->0.1437	0.0963->0.1437
Annuity variant outcome	6.51 (+3%)	5.44 (+6%)	6.14 (+3%)
Biomass feedstock price +10 €/ton dry mass	15->25	9->19	30->40
Biomass feedstock variant outcome	7.01 (+11%)	5.81 (+13%)	6.57 (+10%)
Using grid electricity in €/GJe	13.6->30	9.4->30	13.6->30
Grid electricity variant outcome	7.22 (+15%)	6.75 (+31%)	6.55 (+9%)
Sea transport like coal transport costs in €/ton	43.9->33.0	40.4->29.4	43.9->33.0
Transport variant outcome	5.64 (-10%)	4.50 (-13%)	5.21 (-13%)
Fertilizer range in €/ton feedstock dry basis	4->3-6	7.2->4-12	-
Fertilizer range outcome	6.38-6.12 (+1 - -3%)	5.59-4.47 (+9 - -13%)	-
For EFB no pre dryer needed; outcome	-	4.88 (-5%)	-

As already could be seen in Figure 7, transport has a substantial effect on the pellet price in the Netherlands. If sea transport of pellets reaches the same level as coal, the pellet cost go down substantially. It should be mentioned that there is a storage problem to be solved in the harbour of the producing country and in the Netherlands. The pellets cannot be stored outside for weeks. As already mentioned before the transport costs are in the lower range of the IEA margin [40]. So transport costs will probably be higher instead of lower, certainly during a developing market.

The value of the amount of fertilizer and minerals saved by returning the waste water is substantial for EFB, and there is also a large uncertainty in it. The effect is lower for trash. Is should be mentioned that if the waste water is not returned to the plantation but has to be treated in a waste water treatment plant for 1 €/m^3 costs will raise (with for instance ~5% in case of EFB).

The last variant is related to the EFB route. It looks that EFB might not need a pre-dryer strep after the screw press. It that is the case, investment en operating cost will be lower and less energy is needed. Production costs (incl transport) will then go down with 5%.

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[18] A same calculations for gas comes to 7,1 €/GJ (4.7 fuel and 2.4 CO_2). This is higher than coal, but due its higher efficiency and lower operating cost gas could be cheaper than coal for electricity production in the Netherlands (Status April 2021) depending on the fuel contracts (remark: future prices are used: coal prices are based on delivering in 2022; gas prices on delivering in 2023).

5.5.3 Conclusions based on this TEA

Pellet production and transport to a powerplant nearby Rotterdam harbour in Netherlands result in costs of 6.3 €/GJ for pellets made from gain sugar trash in Brazil, 5.1 €/GJ for pellets made from EFB in Colombia and 6.0 €/GJ for pellets made from bagasse in Brazil. Values are based on the LHV and include transport from a location not too far from a harbour in the producing countries. Costs can be higher if feedstock prices are higher and will probably be higher for transport during market (storage) development (the calculated costs fits better with regular transport and large volumes).
If the screw press can reach a low enough water content in case of EFB, the pre-dryer and first condenser can be skipped, reducing production and transport costs with 5% to 4.9 €/GJ.
Due to the CO_2 trading system in Europe (EU-ETS) those pellets are completely competitive with coal in power plants near Rotterdam with a fuel price of 6.1 €/GJ (including CO_2-costs; March 2021).
The calculated values naturally have the necessary margins of uncertainty, both in current value and in future developments. This TEA does has not investigated or optimized what the best storage method would be. This depends on the number of producers and the port facilities in the country of origin and in Rotterdam.
The TEA showed that the investments have a limited influence on the overall production costs. Domestic transport in the producing countries and sea transport are more important. If domestic transport distances become long, for instance 800 km, it is much better to use rail transport or inland shipping instead of truck transport.
Because the dry weight of the feedstock directly related to the weight of the pellets (with some material losses), feedstock cost have a large effect on the pellet production costs.
Two remarkable things emerge from the analysis.

1. The use of own residual flows for the production of heat and electricity is important for limiting production costs.
2. In addition, the return (recycling) of the wash water from SCT and EFB is important for limiting the loss of fertilizers and minerals. This recycling also has a visible financial advantage.

6 Life cycle analysis of selected CAPCOM pathways

6.1 Goal of the LCA study

The goal of this study is to assess the overall GHG impacts of a possible supply chain of selected CAPCOM pathways:

- Sugarcane bagasse pellets from Brazil
- Sugarcane trash pellets from Brazil
- Empty fruit bunch pellets from Colombia

And compare with the GHG impacts of wood pellets from North America. Furthermore, it is aimed to calculate the GHG impacts with the inclusion of the transportation of CAPCOM pellets to the Netherlands and conversion to end product which is either power or bioethanol. And compare the impacts with the fossil fuel comparator for electricity and biofuels.

6.2 Scope definition

The impact category considered is Global Warming Potential (GWP). It is considered to follow the GHG emissions accounting methodology described in the REDII[19]. This is because for carrying out the comparisons wood pellet impacts and fossil fuel comparators provided in this directive are considered. For comparability the same methodological choices need to be made (e.g. system boundary, functional unit, allocation method, impact assessment method). Accordingly, it is considered to use energy allocation between co-products. For cogeneration of heat and electricity, REDII prescribes the use of exergy allocation to allocate the emissions between electricity and useful heat. Additionally, REDII considers residues to have zero life-cycle greenhouse gas emissions up to the process of collection of those materials. Therefore, in the inventory analysis and impact assessment, a stage for production of residues is not included and the product system starts with collection of residues. However, in the interpretation phase also the consequences of removing the residues from the current system are elaborated.

The geographical scope is production of the bagasse and sugarcane trash pellets in Brazil, EFB pellets in Colombia and their conversion and use in the Netherlands. Temporal scope is current production. The technical scope is current commercial technologies with relevant technological developments foreseen in the near future (5 years).

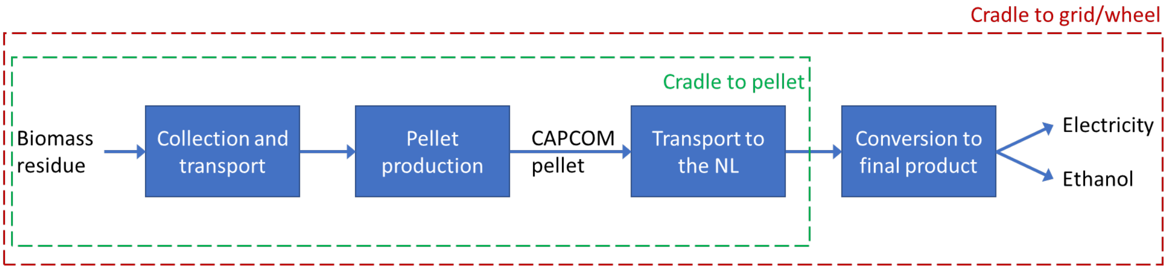

Figure 8 System boundaries of studied CAPCOM pellet product systems

Two different system boundaries are considered in this study, one stopping at the pellet product and the other considering its conversion into end product. Two different end products are considered from conversion of pellets which are electricity and ethanol.

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[19] European Commission, 2018. Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)

The specific stages considered are (see Figure 8):

- Collection and transportation of residue
- Pellet production
- Transportation of pellets
- Conversion to final product (electricity or ethanol)

The functional unit is the production of 1 MJ pellet. With the inclusion of conversion to the final products, the functional unit is 1 MJ final energy (electricity or ethanol).

The studied product systems are shown in Table 14. Product systems include the selected feedstocks for pellet production as well as further conversion of the pellets for electricity and ethanol production. For pellet production comparison is done with the reference wood pellets produced in North America. For the end products comparison is made with the electricity and fuel produced from fossil resources.

Table 14 CAPCOM product systems studies

Pathways	***Product systems***
Bagasse	Bagasse pellet production in Brazil
	Bagasse pellet for electricity production in Netherlands
	Bagasse pellet for ethanol production in Netherlands
Sugarcane trash	Sugarcane trash pellet production in Brazil
	Sugarcane trash pellet for electricity production in Netherlands
	Sugarcane trash pellet for ethanol production in Netherlands
Empty fruit bunch	EFB pellet production in Colombia
	EFB pellet for electricity production in Netherlands
	EFB pellet for ethanol production in Netherlands
Reference pellet system	Wood pellet production in North America
Reference fossil electricity and liquid fuel	Fossil fuel comparator for electricity Fossil fuel comparator for biofuels

6.3 Life cycle inventory analysis

Life cycle inventory tables for the investigated CAPCOM pellet production chains are provided in Annex A.

6.3.1 Sugarcane bagasse product system

6.3.1.1 Collection and transportation of bagasse to pellet production

Bagasse is a process residue which is attained in the sugar mill. Therefore, it is not required to collect and transport it from the sugarcane fields (unlike sugarcane trash). It is considered that the production of pellets is located at the sugar mill. No road transportation of bagasse is therefore required. This is already commercially applied by Raizen at its production plant near Jau in Sao Paulo state.[20]

6.3.1.2 Pellet production from bagasse

This process includes the operations of steam explosion, drying and pelletizing. The overall energy demand for these processes are compiled in Table 15 after considering internal heat integration possibilities. The bagasse delivered at 50% moisture content is dried down to 10% in forming the pellet. LHV of bagasse pellet is 19.2 MJ/kg[21].

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[20] https://www.raizen.com.br/en

[21] CAPCOM project direct measurement VIR 0026

Table 15 Input data for bagasse pellet production

	Amount	*Unit*
Input		
Bagasse	1.11	$MJ_{bagasse}$
Heat	165.1	kJ
Electricity	34.5	kJ
Output		
Bagasse pellet	1	MJ_{pellet}

As it is considered that the production of pellets is carried out in the sugar mill, mill's internal energy production system is considered which utilizes own bagasse for energy. Typically, energy generation in most sugarcane mills is based on cogeneration cycles which are able to meet the whole energy demand of the mills and still produce some bagasse and electricity surpluses. Seabra et al. reports that in overall an average 10.7 kWh/t of sugarcane as surplus electricity have been sold to the electric grid [41]. The average for mills already connected to the grid and selling power was reported as 28 kWh/t cane with some mills selling more than 60 kWh/t cane.[22] There is potential to increase further with modernization and process improvements in the near future, especially considering the use of trash as additional fuel to bagasse {Seabra, 2011 #77}.**Fout! Bladwijzer niet gedefinieerd.**

The bagasse pellet production scale is considered as 20 t/h which requires 3.3 MW electricity:

$$34.5\,\frac{kJ_e}{MJ}\times 19.2\frac{MJ}{kg}\times 0.9\times 20\frac{t}{h}\times\frac{h}{3600\,s}\times\frac{1000\,kg}{1\,t}\times\frac{MJ}{1000\,kJ}=3.3\,MW$$

This corresponds to 11.3 kWh/t cane considering reference plant cane production of 292 t/h.[22]

$$3.3\,MW\times\frac{h}{292\,t}\times\frac{1000\,kW}{1\,MW}=11.3\frac{kWh}{t_{cane}}$$

This means that it is expected that the surplus electricity available from the sugarcane mill is sufficient to supply the demand of CAPCOM bagasse pellet production.

Regarding the heat demand this can be supplied by using the surplus bagasse. The amount of heat required to be supplied by bagasse can be calculated as:

$$165.1\,\frac{kJ_h}{MJ}\times 19.2\frac{MJ}{kg}\times 0.9\times 20\frac{t}{h}\times\frac{h}{3600\,s}\times\frac{1000\,kg}{1\,t}\times\frac{MJ}{1000\,kJ}=15.8\,MW$$

This heat demand can be supplied with a bagasse boiler with 85% efficiency. The amount of bagasse (at 50% moisture) required to supply this heat demand is:

$$15.8\,MW\times\frac{1}{0.85}\times\frac{h}{292\,t}\times\frac{3600\,s}{1\,h}\times\frac{kg}{19.2\,MJ}\times\frac{1}{0.5}=23.9\frac{kg}{t_{cane}}$$

Macedo et al. considers 9.6 % of bagasse to be surplus [42]. Considering a bagasse content of 26.4% {Seabra, 2011 #77}**Fout! Bladwijzer niet gedefinieerd.**, amount of surplus bagasse available is 25.3 kg per t cane. This is also in line with the value of 26.7 kg per t cane reported in NL Agency report.[22]

This calculation shows that the surplus electricity and bagasse available in current sugarcane mills is sufficient to cover the energy demands of CAPCOM bagasse pellet production. However, as there is bagasse required to produce the pellets themselves there needs to be additional bagasse available for that. The possibilities for freeing up additional bagasse from sugarcane mills is described in discussion section.

According to the methodology set in RED II, there is no allocation of any emissions to residues like straw or bagasse. Therefore, all the emissions from sugar cane production and processing are allocated to ethanol. Internal bagasse CHP satisfies the steam demand and produces surplus electricity which is exported to the grid. The surplus bagasse is considered available free of burden and electricity exported is considered free of emissions from bagasse or straw provision.

However, the non-CO_2 emissions during combustion need to be allocated between exported electricity and ethanol. This needs to be allocated based on exergy according to RED II. Furthermore, emissions associated with bagasse boiler to produce heat needs to accounted for.

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[22] NL Agency (2012) Improving the sustainability of the Brazilian sugar cane industry. Utrecht. The Netherlands.

Emissions associated with bagasse CHP and bagasse boiler are provided in Table 16.

Table 16 Bagasse CHP and boiler emissions[23]

Bagasse CHP	*Amount*	*Unit*
Input		
Bagasse	1	MJ
Output		
CH_4	2.5×10^{-3}	g
N_2O	1.2×10^{-3}	g
Bagasse boiler	*Amount*	*Unit*
Input		
Bagasse	1	MJ
Output		
CH_4	1.7×10^{-3}	g
N_2O	0.7×10^{-3}	g

6.3.2 Sugarcane trash product system

6.3.2.1 Collection and transportation of sugarcane trash to pellet production

Baling is often used for harvesting residues recovery with increase in density and transformation of the biomass in uniform units (bales). It can be applied to recover sugarcane trash after unburned cane harvesting. The percentage of trash recovered in relation to available trash in the field after unburned cane harvesting can be up to 88%.[24] The 24% of trash from field is transported with sugarcane to the mill. This amount is considered to be freely available at the mill. Remaining 64% trash is recovered from the field through baling and transporting to the mill. The impacts associated with these processes need to be taken into consideration. At the mill, a trash processing system is needed to grind this residue to a particle size and density condition where it can be handled.

Baling:
Diesel consumption: 1.5 L/t dry trash[24]
For correction for the % that needs to be baled from field, this needs to be multiplied with a factor of 64/88 as described above.
Diesel LHV (volume): 36 MJ/L[23]
Dry SCT LHV: 18.18 MJ/kg[25]
Diesel use for baling can accordingly be calculated as:

$$1.5\frac{L}{t_{dry\ trash}}x\frac{64}{88}x36\frac{MJ}{L}x\frac{kg}{18.18\ MJ}x\frac{t}{1000\ kg}=0.002\frac{MJ_{diesel}}{MJ_{SCT}}$$

Emission factors for the Diesel: 95.1 g CO_2eq/MJ[23].

Truck transport:
The common means of transport considered for road transportation is 40 tonnes truck with a payload of 27 tonnes.
Distance: 21 km
Dry matter content: 85%

The transportation demand can be calculated as:

$$21km\times\frac{kg\ dry}{18.18\ MJ}\times\frac{1\ kg\ total}{0.85\ kg\ dry}\times\frac{1\ t}{1000\ kg}=0.00136\frac{tkm}{MJ_{SCT}}$$

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[23] Giuntoli, J., Agostini, A., Edwards, R., & Marelli, L. (2017). Solid and gaseous bioenergy pathways. Input values and GHG emissions. [Excel file] Full Dataset.

[24] CA Sarto, SJ Hassuani (2005). 8. Trash recovery: Baling machines in *Biomass power generation: sugar cane bagasse and trash*. Ed: Suleiman José Hassuani, Manoel Regis Lima Verde Leal, Isaías de Carvalho Macedo. PNUD-CTC.

[25] CAPCOM project direct measurement VIR 0030

The fuel consumption and emissions associated with road transport are provided in Table 17.

Table 17 Fuel consumption and emissions for road transport[23]

	Amount	*Unit*
Input		
Diesel	0.811	MJ/tkm
Output		
Distance	1	tkm
CH_4	0.0034	g/tkm
N_2O	0.0015	g/tkm

6.3.2.2 Pellet production from sugarcane trash

The bales are fed to the system through a feeding table and belt conveyor. SCT follows the process steps of size reduction, CC SMB extraction, screw press, pre-dryer, steam explosion, post-dryer and pellet press to form the SCT pellets. The overall energy demand from these processes are compiled in Table 18 after considering internal heat integration possibilities. The LHV (dry) of SCT is 18.18 MJ/kg.

Table 18 Input data for SCT pellets production

	Amount	*Unit*
Input		
SCT	1.32	MJ_{SCT}
Heat	263.3	kJ
Electricity	57.3	kJ
Output		
SCT pellet	1	MJ_{pellet}

As it is considered that the production of pellets is carried out in the sugar mill, mill's internal energy production system is considered which utilizes own bagasse for energy. As explained above typically in most sugarcane mills some bagasse and electricity surpluses exist. It is assessed below whether this is sufficient to cover the energy demand of CAPCOM SCT pellet production.

The SCT pellet production scale is considered as 30 t/h which requires 7.8 MW electricity:

$$57.3\,\frac{kJ_e}{MJ}\times 18.18\frac{MJ}{kg}\times 0.9\times 30\frac{t}{h}\times\frac{h}{3600\,s}\times\frac{1000\,kg}{1\,t}\times\frac{MJ}{1000\,kJ}=7.8\,MW$$

This corresponds to 11.3 kWh/t cane considering reference plant cane production of 292 t/h[22].

$$7.8\,MW\times\frac{h}{292\,t}\times\frac{1000\,kW}{1\,MW}=26.7\frac{kWh}{t_{cane}}$$

Since the average surplus electricity was reported as 28 kWh/t cane[22], it can be expected that there is sufficient availability to supply the electricity demand of CAPCOM bagasse pellet production.

The heat demand can be calculated as:

$$263.3\,\frac{kJ_h}{MJ}\times 18.18\frac{MJ}{kg}\times 0.9\times 30\frac{t}{h}\times\frac{h}{3600\,s}\times\frac{1000\,kg}{1\,t}\times\frac{MJ}{1000\,kJ}=35.9\,MW$$

This heat demand can be supplied with a bagasse boiler with 85% efficiency. The amount of bagasse (at 50% moisture) required to supply this heat demand is:

$$35.9\,MW\times\frac{1}{0.85}\times\frac{h}{292\,t}\times\frac{3600\,s}{1\,h}\times\frac{kg}{19.2\,MJ}\times\frac{1}{0.5}=54.2\frac{kg}{t_{cane}}$$

The required amount of bagasse is likely to be more than surplus bagasse available in average sugarcane mills which was reported to be around 26 kg per t cane as described above. However, new mill units are already equipped with high-pressure steam systems (e.g. 6.5 MPa/480°C; some units with 9.0MPa) {Macedo, 2008 #78}.**Fout! Bladwijzer niet gedefinieerd.** The improved steam cycles are reported to result in surplus bagasse of over 50 kg per t cane to be available in mills.[22] Which shows that, by

also considering possible process improvements, the heat demand of CAPCOM bagasse pellet production can be met especially considering the possible use of trash as additional fuel to bagasse. The surplus bagasse is considered available free of burden and electricity exported is considered free of emissions from bagasse or straw provision. However, the non-CO_2 emissions during combustion need to be allocated between exported electricity and ethanol. Furthermore, emissions associated with bagasse boiler to produce heat needs to accounted for.
Counter current simulated moving bed (CC SMB) is used to extract minerals from SCT. Subsequently, screw press removes the water containing minerals and this can be returned to the field. The amount of returned nutrients is given in Table 19.

Table 19 Nutrients extracted and returned to field

	Amount	*Unit*
KCl	5.82×10^{-4}	kg/MJ pellet
P	8.03×10^{-8}	kg/MJ pellet

This provides a possibility to reduce input of artificial fertilizers which can be assigned as a possible credit. The nutrients returned displace marginal P and K fertilizers P_2O_5 and K_2O respectively. The associated GHG savings can be calculated using emission factor for P_2O_5 of 541.7 g CO_2eq/kg and K_2O of 416.7 g CO_2eq/kg.[23]

6.3.3 Empty fruit bunch product system

6.3.3.1 Collection and transportation of EFB to pellet production

EFB is a process residue which is attained in the palm oil mill. Therefore, it is not required to collect and transport it from the fields. It is considered that the production of pellets is located at the palm oil mill. No road transportation of EFB is therefore required.

6.3.3.2 Pellet production from EFB

EFB follows the process steps of size reduction, CC SMB extraction, screw press, pre-dryer, steam explosion, post-dryer and pellet press to form the EFB pellets. The overall energy demand from these processes are compiled in Table 20 after considering internal heat integration possibilities. It is considered that the EFB is pressed in the palm oil mill and it is available at a dry matter content of 45% for the counter correct extraction. The attained pellets have a 10% moisture content and have LHV (dry) of 19 MJ/kg[26].

Table 20 Input data for EFB pellets production

	Amount	*Unit*
Input		
EFB	1.27	MJ_{EFB}
Heat	211.6	kJ
Electricity	77.6	kJ
Output		
EFB pellet	1	MJ_{pellet}

As it is considered that the production of pellets is carried out in the palm oil mill, mill’s internal energy production system is considered which utilizes own mesocarp fibre and palm kernel shells for energy. Typically in most palm oil mills there is a surplus of mesocarp fibre and palm kernel shells. This is provided to be about 50-75 kg/t FFB [36][27]. Furthermore, excess electricity can be available in mills. The practice of cogeneration has been used in most mills more with the intention of meeting the energy needs in the process of extraction of crude palm oil, rather than as a source of extra income by exporting electricity to the grid. Accordingly, electricity generated has a low efficiency.

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[26] CAPCOM project direct measurement VIR 00304

[27] Edwards, R., Padella, M., Giuntoli, J., Koeble, R., O’Connell, A., Bulgheroni, C., Marelli, L. 2017. Definition of input data to assess GHG default emissions from biofuels in EU legislation, version 1c. JRC Science for Policy Report.

It is estimated that currently about 14 kWh/t FFB surplus electricity is available. There has been a significant change in technology in recent years by using high-pressure boilers, which could generate more electricity estimated to exceed 75 kWh/t FFB [16].
It is assessed below whether the available surplus electricity and biomass is sufficient to cover the energy demand of CAPCOM EFB pellet production.

The feedstock input of 10 t/h EFB (45% moisture) is considered which corresponds to EFB pellet production scale of 3.9 t/h. The electricity required is:

$$77.6\,\frac{kJ_e}{MJ} \times 19\,\frac{MJ}{kg} \times 0.9 \times 3.9\,\frac{t}{h} \times \frac{h}{3600\,s} \times \frac{1000\,kg}{1\,t} \times \frac{MJ}{1000\,kJ} = 1.4\,MW$$

This corresponds to 48.2 kWh/t FFB considering reference plant capacity of 60 t FFB/h {Garcia-Nunez, 2016 #5}.

$$1.4\,MW \times \frac{h}{60\,t} \times \frac{1000\,kW}{1\,MW} = 24.1\,\frac{kWh}{t_{FFB}}$$

The required surplus electricity is likely to be more than available in palm oil mills which was reported to be around 14 kWh/t FFB as described above. However, new mill units are already equipped with higher efficiency boilers and turbines {Arrieta, 2007 #79}. Arrieta et al. in a comparative study conducted in Colombia, indicate that the cogeneration in mills with a FFB processing capacity of 18–60 t FFB/h, have a potential to provide a surplus electricity from 1 to 7 MW [43]. This shows that the electricity demand of CAPCOM EFB pellet production can be met. There is also additional possibility to produce biogas from POME in mills and use it as additional source for electricity production besides fiber and shells.

The heat demand can be calculated as:

$$211.6\,\frac{kJ_h}{MJ} \times 19\,\frac{MJ}{kg} \times 0.9 \times 3.9\,\frac{t}{h} \times \frac{h}{3600\,s} \times \frac{1000\,kg}{1\,t} \times \frac{MJ}{1000\,kJ} = 3.9\,MW$$

This heat demand can be supplied with a boiler using the surplus mesocarp fiber and palm kernel shells with 85% efficiency. The calorific value of the dry biomass is: fiber 18.6 MJ/kg; shells 20.8 MJ/kg [28]. The moisture content of fiber and shell are 35% and 14% respectively {Garcia-Nunez, 2016 #5}. Accordingly, considering LHV of wet biomass of average 15 MJ/kg, the amount of biomass required to supply this heat demand is:

$$3.9\,MW \times \frac{1}{0.85} \times \frac{h}{60\,t} \times \frac{3600\,s}{1\,h} \times \frac{kg}{15\,MJ} = 18.5\,\frac{kg}{t_{FFB}}$$

This means that it is expected that the surplus fibers and shells available from the palm oil mill is sufficient to supply the heat demand of CAPCOM EFB pellet production. The baseline case provided in Garcia-Nunez et al. produce 35.6 kg fiber/t FFB and 13.9 kg shells/t FFB {Garcia-Nunez, 2016 #5}. This corresponds to a heat content of 11 MW which is significantly higher than required to supply the 3.9 MW heat demand of this process. Additionally, it could be considered to use turbines in combination with boilers to generate electricity to supply part of the electricity demand of the process. This calculation shows that the surplus electricity and biomass (fiber and shells) available in palm oil mills are sufficient to cover the energy demands of CAPCOM EFB pellet production. According to the methodology set in RED II, the surplus biomass (fiber and shells) is considered available free of burden and electricity surplus is considered free of emissions from fuel provision.
However, the non-CO_2 emissions during combustion need to be allocated between exported electricity and crude palm oil. This needs to be allocated based on exergy according to RED II. Furthermore, emissions associated with biomass (fiber and shells) boiler to produce heat needs to accounted for.

Emissions associated with shells and fibers combustion are provided in Table 21.

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[28] www.searates.com

Table 21 Emissions from fiber and shells combustion

CHP[27]	*Amount*	*Unit*
Input		
Biomass (fiber and shells)	1	MJ
Output		
CH_4	3×10^{-3}	g
N_2O	4×10^{-3}	g
Boiler[23]	*Amount*	*Unit*
Input		
Bagasse	1	MJ
Output		
CH_4	1.7×10^{-3}	g
N_2O	0.7×10^{-3}	g

Counter current simulated moving bed (CC SMB) is used to extract minerals from EFB. Subsequently, screw press removes the water containing minerals and this can be returned to the field. The amount of returned nutrients is given in Table 22.

Table 22 Nutrients extracted from EFB and returned to field

	Amount	*Unit*
KCl	2.40×10^{-3}	kg/MJ pellet
P	6.62×10^{-5}	kg/MJ pellet

This provides a possibility to reduce input of artificial fertilizers which can be assigned as a possible credit. The nutrients returned displace marginal P and K fertilizers marginal P and K fertilizers P_2O_5 and K_2O respectively. The associated GHG savings can be calculated using emission factor for P_2O_5 of 541.7 g CO_2eq/kg and K_2O of 416.7 g CO_2eq/kg. [23]

6.3.4 Conversion of CAPCOM pellets to final product

6.3.4.1 Transportation of pellets to the Netherlands

Sugarcane trash and bagasse pellets from Brazil

The bagasse pellets and SCT pellets are then transported from Brazil to the Netherlands. This includes:

- road transportation of pellets from the mill to the port in Brazil
- transoceanic transportation from port in Brazil to the port in Netherlands
- barge transportation from port to the power plant in the Netherlands

It is assumed that the production of pellets is located in the central part of Sao Paulo State. The distance is 400 km from central Sao Paulo State to Porto de Santos.
The transportation demand per MJ bagasse pellet is :

$$400km \times \frac{kg\ dry}{19.2MJ} \times \frac{1\ kg\ total}{0.9\ kg\ dry} \times \frac{1\ t}{1000\ kg} = 0.023 \frac{tkm}{MJ}$$

The transportation demand per MJ SCT pellet is :

$$400km \times \frac{kg\ dry}{18.2MJ} \times \frac{1\ kg\ total}{0.9\ kg\ dry} \times \frac{1\ t}{1000\ kg} = 0.025 \frac{tkm}{MJ}$$

The fuel consumption and emissions associated with road transport are provided in Table 17.

Pellets shipped to Europe from longer distances (e.g. > 8000 km) are assumed to be transported via Supramax bulk carriers of 57000 dry weight tonnes and 54000 tonnes of net payload. The distance from Porto de Santos in São Paulo State (BR) to the Port of Rotterdam (NL) is 10050 km.[29]

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[29] www.searates.com

The fuel consumption are calculated by the JRC via data provided by the International Maritime Organization. This is attained from Giuntoli *et al.* (2017) and provided in Table 23.[23] The transportation demand per MJ bagasse pellet is :

$$10050km \times \frac{kg\ dry}{19.2MJ} \times \frac{1\ kg\ total}{0.9\ kg\ dry} \times \frac{1\ t}{1000\ kg} = 0.581 \frac{tkm}{MJ}$$

The transportation demand per MJ SCT pellet is :

$$10050km \times \frac{kg\ dry}{18.2MJ} \times \frac{1\ kg\ total}{0.9\ kg\ dry} \times \frac{1\ t}{1000\ kg} = 0.614 \frac{tkm}{MJ}$$

Table 23 Fuel consumption for Supramax bulk carrier[27]

	Amount	*Unit*
Input		
Heavy fuel oil	0.0656	MJ/tkm
Output		
Distance	1	tkm

The pellets then need to be transported to power plants. The RWE Amer power plant in Geertruidenberg in Noord-Brabant has already been converted into a biomass power plant. Over 50% of the hard coal is being replaced by biomass on a daily basis. By the end of 2020 this percentage will be increased to 80% or more.[30] Transportation from the port of Rotterdam to Amer power plants can take place via barge ship on a distance of 50 km. Just like the Amer power station, the Eemshaven power station is being converted into a biomass power station. At present, 15% of the energy is generated by biomass.[31] The transportation of pellets take place through coasters over 360 km.
For simplicity the Amer plant is considered for transportation emission calculations which considers barge transport to a 50 km distance. The barge transport fuel consumption and emissions are attained from Edwards *et al.* (2017) and are provided in Table 24.[27] The transportation demand per MJ bagasse pellet is :

$$50km \times \frac{kg\ dry}{19.2MJ} \times \frac{1\ kg\ total}{0.9\ kg\ dry} \times \frac{1\ t}{1000\ kg} = 0.0029 \frac{tkm}{MJ}$$

The transportation demand per MJ SCT pellet is :

$$50km \times \frac{kg\ dry}{18.2MJ} \times \frac{1\ kg\ total}{0.9\ kg\ dry} \times \frac{1\ t}{1000\ kg} = 0.0031 \frac{tkm}{MJ}$$

Table 24 Fuel consumption and emissions for barge transport[27]

	Amount	*Unit*
Input		
Diesel	0.324	MJ/tkm
Output		
Distance	1	tkm
CH_4	0.093	g/tkm
N_2O	0.0004	g/tkm

Emission factors for the fuels used are: Diesel 95.1 g CO_2eq/MJ and Heavy fuel oil 94.2 g CO_2eq/MJ. [27]

EFB pellets from Colombia

The EFB pellets are transported from Colombia to the Netherlands. This includes:

- rail transportation of pellets from the mill to the port in Colombia
- transoceanic transportation from port in Colombia to the port in Netherlands
- barge transportation from port to the power plant in the Netherlands

It is assumed that the production of pellets is located in Fundación, in the Magdalena region. The distance is about 100 km to the port of Santa Marta and a railroad freight transport is available.[32]

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[30] https://www.group.rwe/en/our-portfolio/our-sites/amer-power-plant

[31] https://www.group.rwe/en/our-portfolio/our-sites/eemshaven-power-plant

[32] https://www.fenoco.com.co/index.php/mapa-ferroviario

The transportation demand per MJ EFB pellet is :

$$100km \times \frac{kg\ dry}{19\ MJ} \times \frac{1\ kg\ total}{0.9\ kg\ dry} \times \frac{1\ t}{1000\ kg} = 0.006\frac{tkm}{MJ}$$

The fuel consumption and emissions associated with rail transport are provided in Table 25.

Table 25 Fuel consumption and emissions for rail transport

	Amount	*Unit*
Input		
Diesel	0.252	MJ/tkm
Output		
Distance	1	tkm
CH_4	0.005	g/tkm
N_2O	0.001	g/tkm

Pellets shipped to Europe from longer distances (e.g. > 8000 km) are assumed to be transported via Supramax bulk carriers of 57000 dry weight tonnes and 54000 tonnes of net payload. The distance from Port of Santa Marta (CO) to the Port of Rotterdam (NL) is 8470 km.[29] The fuel consumption are provided in Table 23.

The transportation demand per MJ EFB pellet is:

$$8470km \times \frac{kg\ dry}{19\ MJ} \times \frac{1\ kg\ total}{0.9\ kg\ dry} \times \frac{1\ t}{1000\ kg} = 0.494\frac{tkm}{MJ}$$

The EFB pellets then need to be transported to power plant from Rotterdam port with barge transport to a 50 km distance similar to the bagasse pellet and SCT pellet described above. The barge transport fuel consumption and emissions are provided in Table 24. The transportation demand per MJ EFB pellet is:

$$50km \times \frac{kg\ dry}{19\ MJ} \times \frac{1\ kg\ total}{0.9\ kg\ dry} \times \frac{1\ t}{1000\ kg} = 0.0029\frac{tkm}{MJ}$$

6.3.4.2 Electricity production

In both Amer and Eemshaven power plants the pellets are brought to the plant using a pneumatic transport system and stored in silos. They are co-combusted with coal that is pulverized in roller mills and injected with combustion air into the high temperature supercritical steam boilers. Electricity is consumed due to grinding of the pellets of 50 kWh/tonne pellet [44]. The Amer plant is a cogeneration plant producing electricity and heat. The heat generated is used for district heating.[30] The electrical efficiency is about 41%. The Eemshaven plant comprises two boiler with an efficiency level of 46%.[31] In this study, only electricity generation is considered with a more conservative 41% efficiency.

Table 26 Co-firing in power plant inventory data

	Amount	*Unit*
Input		
Electricity	0.0094	MJ_e/MJ pellet
Bagasse/EFB/SCT pellet	1	MJ
Output		
Electricity	0.41	MJ_e/MJ pellet
CH_4*	0.0009	g/MJ pellet
N_2O*	0.0014	g/MJ pellet

* Emission data for wood pellet co-combustion (pulverized coal-fired power plant) is used due to unavailability of data for bagasse pellets.[33]

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[33] Biograce II, https://www.biograce.net/app/webroot/biograce2/content/ghgcalculationtool_electricityheatingcooling/overview

Emission factor for the Netherlands grid electricity[34]: 164 gCO_2eq/MJ_e

6.3.4.3 Ethanol production

Only initial tests in lab scale have been carried out for the conversion of CAPCOM pellets to ethanol. To be able to assess the GHG emissions from the conversion to ethanol literature data were used. For this Maga *et al.* [46]. was used as reference which considers stand-alone production of ethanol using bagasse (4.68 kg/L ethanol) and straw (1.68 kg/L ethanol) as feedstock. For inventory data the reader can refer to this study which has been carried out based on the experimental results attained from EU project ProEthanol2G. The whole process was modelled using process simulation and covers 9 unit processes: P1) bagasse and trash provision (P1a) trash harvesting from field, loading, and transportation, (P1b) trash cleaning and milling, (P2) biomass pretreatment, (P3) on-site enzyme production, (P4) enzymatic hydrolysis, (P5) yeast propagation; (P6) C5/C6 sugar fermentation; (P7) distillation and dehydration, (P8) wastewater treatment, and (P9) steam and power generation. Emission associated with stages P1 and P2 are already accounted for above so only the downstream sections are considered. Enzyme production (P3) considers production of enzyme on-site using 8.25% of total solids from biomass pretreatment and input of chemicals (including ammonium sulphate, ammonia, calcium chloride). The enzymatic hydrolysis (P4) is considered to have a 80% yield for cellulosic and hemicellulosic fractions. In (P5) molasses and ammonium phosphate are used for yeast propagation. For the C5/C6 sugar fermentation (P6) process, an industrial recombinant yeast, able to ferment glucose (C6) and xylose (C5) from 2G hydrolysates, is used. The yields of 0.45 and 0.35 g/g of ethanol from glucose and xylose, respectively, are considered. Organic content from filtrates and stillage is anaerobically digested to biogas in the wastewater treatment unit (P8). In the steam and power generation process (P9) lignin cake obtained after enzymatic hydrolysis, yeast cake from ethanol fermentation (P6), fungi cake from on-site enzyme production (P3) and biogas generated in the wastewater treatment (P8) are co-fired in order to produce steam and electricity. No external energy input is thereby required.

The results from this study are directly applicable for bagasse and SCT feedstocks. The overall ethanol yield is provided to be 0.22 kg ethanol/kg biomass (dry). This is in line with the values calculated considering 39.8% cellulose and 26.5% hemicellulose content on dry weight.[35]

Ethanol yield:

$$\left(0.398\frac{kg_{cellulose}}{kg_{bagasse}}\times 0.8\frac{kg_{glucose}}{kg_{cellulose}}\times 0.45\frac{kg_{ethanol}}{kg_{glucose}}\right)+\left(0.265\frac{kg_{hemicellulose}}{kg_{bagasse}}\times 0.8\frac{kg_{xylose}}{kg_{hemicellulose}}\times 0.35\frac{kg_{ethanol}}{kg_{xylose}}\right)$$
$$=0.217\frac{kg_{ethanol}}{kg_{bagasse}}$$

For EFB own measurements from CAPCOM project available following hydrolysis were considered. 0.385 kg glucose and 0.206 kg xylose per kg EFB dry matter is reported.[36] The ethanol yield can be calculated following same yield information as:

Ethanol yield:

$$\left(0.385\frac{kg_{glucose}}{kg_{EFB}}\times 0.45\frac{kg_{ethanol}}{kg_{glucose}}\right)+\left(0.206\frac{kg_{xylose}}{kg_{EFB}}\times 0.35\frac{kg_{ethanol}}{kg_{xylose}}\right)=0.245\frac{kg_{ethanol}}{kg_{EFB}}$$

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[34] Ecoinvent 3.6, Electricity, high voltage 45. Seader, J.D. and E.J. Henly, *Separation process principles*. 1998: John Wiley & Sons.| market for | APOS, S

[35] In the Phyllis2 database (www.phyllis.nl) an average was taken of samples 1049, 1050, 2567 and 2535.

[36] Personal communication Johan van Groenestijn, 12 April 2021.

6.4 Life cycle impact assessment

Based on the REDII methodology, greenhouse gas emissions from the production and use of biomass fuels before conversion into electricity, heating and cooling, shall be calculated as:

$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} – e_{ccs} - e_{ccr}$,

Where:

E = total emissions from the production of the fuel before energy conversion;

e_{ec} = emissions from the extraction or cultivation of raw materials;

e_l = annualised emissions from carbon stock changes caused by land-use change;

e_p = emissions from processing;

e_{td} = emissions from transport and distribution;

e_u = emissions from the fuel in use;

e_{sca} = emission savings from soil carbon accumulation via improved agricultural management;

e_{ccs} = emission savings from CO_2 capture and geological storage; and

e_{ccr} = emission savings from CO_2 capture and replacement.

Since, bagasse, SCT and EFB are residues, according to REDII, no emissions allocated from cultivation and accordingly e_{ec} is considered to be zero. Furthermore, emissions from land-use change (e_l) and emissions savings from soil carbon accumulation (e_{sca}) and from CO_2 capture (e_{ccs} and e_{ccr}) are not applicable to this assessment.

Accordingly, the calculation is simplified into:

$E = e_p + e_{td} + e_u$

The impact assessment can accordingly be divided into three parts:

- Processing emissions
- Transport emissions
- End use emissions

6.4.1 Processing to pellet

6.4.1.1 Bagasse pellets

Energy use

Surplus electricity

The non-CO_2 emissions from sugarcane ethanol production during combustion need to be allocated by exergy between mill's own energy needs and surplus electricity. The fraction of bagasse-burning emissions allocated to electricity export can be calculated using the reference mill information provided in NL Agency report[22]:

Efficiency boiler: 71%
Efficiency turbine: 8%
Mill's own electricity demand: 43.2 MJ/t cane
Mill's own heat demand: 1.27 GJ/t cane
Surplus electricity: 67.3 MJ/ t cane
Overall thermal efficiency: 65.3 %
Overall electrical efficiency: 5.7%

For calculation of useful heat Carnot efficiency is used:

C_h =Carnot efficiency in heat at 150 °C (423.15 kelvin) is: 0.3546

Allocation factor electricity =

$$\frac{\eta_{el}}{(\eta_{el} + \eta_h \times C_h)} = \frac{0.057}{(0.057 + 0.653 \times 0.3546)} = 0.197$$

Allocation factor heat =

$$\frac{\eta_h \times C_h}{(\eta_{el} + \eta_h \times C_h)} = \frac{0.653 \times 0.3546}{(0.057 + 0.653 \times 0.3546)} = 0.803$$

Table 27 Emissions from bagasse CHP

	Amount	*Unit*	*Emission factor*	*Unit*	*GHG emissions*	
CH_4	2.5×10^{-3}	g/MJ$_{bagasse}$	25	gCO_2/gCH_4	0.063	$gCO_2eq/MJ_{bagasse}$
N_2O	1.2×10^{-3}	g/MJ$_{bagasse}$	298	gCO_2/gN_2O	0.357	$gCO_2eq/MJ_{bagasse}$
Total					0.420	$gCO_2eq/MJ_{bagasse}$

Emissions associated with surplus electricity to supply CAPCOM process electricity demand is:

$$0.42\frac{g\ CO_2eq}{MJ_{bagasse}} \times 0.197 \times \frac{MJ_{bagasse}}{0.057\ MJ_e} \times 34.5\ \frac{kJ_e}{MJ_{pellet}} \times \frac{1\ MJ}{1000\ kJ} = 0.050\ \frac{g\ CO_2eq}{MJ_{pellet}}$$

Heat

Table 28 Emissions from bagasse boiler

	Amount	*Unit*	*Emission factor*	*Unit*	*GHG emissions*	
CH_4	1.7×10^{-3}	g/MJ$_{bagasse}$	25	gCO_2/gCH_4	0.042	$gCO_2eq/MJ_{bagasse}$
N_2O	0.7×10^{-3}	g/MJ$_{bagasse}$	298	gCO_2/gN_2O	0.209	$gCO_2eq/MJ_{bagasse}$
Total					0.251	$gCO_2eq/MJ_{bagasse}$

Emissions associated with bagasse boiler to supply CAPCOM process heat demand is:

$$0.251\frac{g\ CO_2eq}{MJ_{bagasse}} \times \frac{MJ_{bagasse}}{0.85\ MJ_h} \times 165.1\ \frac{kJ_h}{MJ_{pellet}} \times \frac{1\ MJ}{1000\ kJ} = 0.049\ \frac{g\ CO_2eq}{MJ_{pellet}}$$

Total emissions associated with energy demand of CAPCOM bagasse pellet production is: 0.1 gCO_2eq/MJ_{pellet}.

Diesel

Additionally, diesel is required for bulldozers for bagasse feeding and trucks for ash removal. The demand is typically 0.0024 MJ diesel per MJ pellet. The emissions associated with diesel use is:

$$0.0024\frac{MJ_{diesel}}{MJ_{pellet}} \times 95.1\frac{g\ CO_2eq}{MJ_{diesel}} = 0.228\frac{g\ CO_2eq}{MJ_{pellet}}$$

Table 29 GHG emissions from processing of CAPCOM bagasse pellets

	GHG emissions, gCO_2eq/MJ_{pellet}
Heat and Electricity	0.1
Diesel	0.228
Total	0.328

6.4.1.2 Sugarcane trash pellets

Collection and transport of SCT from field to pellet production

Baling:

$$0.002\frac{MJ_{diesel}}{MJ_{SCT}} \times 1.32\frac{MJ_{SCT}}{MJ_{pellet}} \times 95.1\frac{g\ CO_2eq}{MJ_{diesel}} = 0.27\frac{g\ CO_2eq}{MJ_{pellet}}$$

Truck transport:

The transport requirement is

$$0.00136\frac{tkm}{MJ_{SCT}} \times 1.32\frac{MJ_{SCT}}{MJ_{pellet}} = 0.0018\frac{tkm}{MJ_{SCT}}$$

Table 30 GHG emissions from transport of SCT to pellet production

	Amount	*Unit*	*Emission factor*	*Unit*	*GHG emissions*	
CH_4	6.12×10^{-6}	g/MJ_{pellet}	25	gCO_2/gCH_4	0.0001	gCO_2eq/MJ_{pellet}
N_2O	2.70×10^{-6}	g/MJ_{pellet}	298	gCO_2/gN_2O	0.0008	gCO_2eq/MJ_{pellet}
Diesel	1.46×10^{-3}	MJ_{diesel}/MJ_{pellet}	95.1	gCO_2/MJ_{diesel}	0.1387	gCO_2eq/MJ_{pellet}
Total					0.14	gCO_2eq/MJ_{pellet}

Total emissions associated with collection and transport of SCT is 0.41 gCO_2eq/MJ_{pellet}.

Energy use

The same methodology described above for bagasse is applied to estimate the GHG emissions from CAPCOM SCT pellet production.

Surplus electricity

Emissions associated with surplus electricity to supply CAPCOM process electricity demand is:

$$0.42\,\frac{g\ CO_2eq}{MJ_{bagasse}}\times 0.197\times\frac{MJ_{bagasse}}{0.057\ MJ_e}\times 57.3\ \frac{kJ_e}{MJ_{pellet}}\times\frac{1\ MJ}{1000\ kJ}=0.083\ \frac{g\ CO_2eq}{MJ_{pellet}}$$

Heat

Emissions associated with bagasse boiler to supply CAPCOM process heat demand is:

$$0.251\,\frac{g\ CO_2eq}{MJ_{bagasse}}\times\frac{MJ_{bagasse}}{0.85\ MJ_h}\times 263.3\ \frac{kJ_h}{MJ_{pellet}}\times\frac{1\ MJ}{1000\ kJ}=0.078\ \frac{g\ CO_2eq}{MJ_{pellet}}$$

Total emissions associated with energy demand of CAPCOM SCT pellet production is: 0.161 gCO_2eq/MJ_{pellet}.

Diesel

Additionally, diesel is required for bulldozers for feeding of feedstock and trucks for ash removal. The demand is typically 0.0024 MJ diesel per MJ pellet. The emissions associated with diesel use is:

$$0.0024\,\frac{MJ_{diesel}}{MJ_{pellet}}\times 95.1\,\frac{g\ CO_2eq}{MJ_{diesel}}=0.228\,\frac{g\ CO_2eq}{MJ_{pellet}}$$

Credit for returned nutrients

GHG emissions savings from returned nutrients can be calculated as:

$$5.82\times10^{-4}\,\frac{kg\ KCl}{MJ_{pellet}}\times\frac{94.2\ kg\ K_2O}{74.5\ kg\ KCl}\times\frac{1}{2}\times 416.7\,\frac{g\ CO_2eq}{kg\ K_2O}=0.153\,\frac{g\ CO_2eq}{MJ_{pellet}}$$

$$8.03\times10^{-8}\,\frac{kg\ P}{MJ_{pellet}}\times\frac{141.9\ kg\ P_2O_5}{31\ kg\ P}\times\frac{1}{2}\times 541.7\,\frac{g\ CO_2eq}{kg\ P_2O_5}=1\times10^{-4}\,\frac{g\ CO_2eq}{MJ_{pellet}}$$

Table 31 GHG emissions from processing of CAPCOM SCT pellets

	GHG emissions, gCO_2eq/MJ_{pellet}
Collection and transport of SCT	0.411
Heat and Electricity	0.161
Diesel	0.228
Credit for returned nutrients	-0.153
Total	0.647

6.4.1.3 EFB pellets

Energy use

Surplus electricity

The non-CO_2 emissions from palm oil production during energy production from fiber and shells in a low pressure boiler and steam turbine need to be allocated by exergy between mill's own energy needs and surplus electricity. The fraction of emissions allocated to electricity export can be calculated using the reference mill information provided in Garcia-Nunez *et al.* {Garcia-Nunez, 2016 #5}:

Efficiency boiler: 73%
Efficiency turbine: 8%
Mill's own electricity demand: 79.2 MJ/t FFB
Mill's own heat demand: 1.276 GJ/t FFB
Surplus electricity: 31 MJ/ t cane
Overall thermal efficiency: 67.2%
Overall electrical efficiency: 5.8%

For calculation of useful heat Carnot efficiency is used:

C_h =Carnot efficiency in heat at 150 °C (423.15 kelvin) is: 0.3546

Allocation factor electricity =

$$\frac{\eta_{el}}{(\eta_{el}+\eta_h \times C_h)} = \frac{0.058}{(0.058+0.672 \times 0.3546)} = 0.114$$

Allocation factor heat =

$$\frac{\eta_h \times C_h}{(\eta_{el}+\eta_h \times C_h)} = \frac{0.672 \times 0.3546}{(0.058+0.672 \times 0.3546)} = 0.886$$

Table 32 Emissions from fiber and shells combustion

	Amount	*Unit*	*Emission factor*	*Unit*	*GHG emissions*	
CH_4	$3\text{x}10^{-3}$	$g/MJ_{\text{fibers\&shells}}$	25	gCO_2/gCH_4	0.075	$gCO_2eq/MJ_{\text{fibers\&shells}}$
N_2O	$4\text{x}10^{-3}$	$g/MJ_{\text{fibers\&shells}}$	298	gCO_2/gN_2O	1.192	$gCO_2eq/MJ_{\text{fibers\&shells}}$
Total					1.267	$gCO_2eq/MJ_{\text{fibers\&shells}}$

Emissions associated with surplus electricity to supply CAPCOM process electricity demand is:

$$1.267\frac{g\ CO_2eq}{MJ_{\text{fibers\&shells}}} \times 0.114 \times \frac{MJ_{\text{fibers\&shells}}}{0.058\ MJ_e} \times 77.6\ \frac{kJ_e}{MJ_{pellet}} \times \frac{1\ MJ}{1000\ kJ} = 0.193\ \frac{g\ CO_2eq}{MJ_{pellet}}$$

Heat

Table 33 Emissions from boiler

	Amount	*Unit*	*Emission factor*	*Unit*	*GHG emissions*	
CH_4	$1.7\text{x}10^{-3}$	$g/MJ_{\text{fibers\&shells}}$	25	gCO_2/gCH_4	0.042	$gCO_2eq/MJ_{\text{fibers\&shells}}$
N_2O	$0.7\text{x}10^{-3}$	$g/MJ_{\text{fibers\&shells}}$	298	gCO_2/gN_2O	0.209	$gCO_2eq/MJ_{\text{fibers\&shells}}$
Total					0.251	$gCO_2eq/MJ_{\text{fibers\&shells}}$

Emissions associated with bagasse boiler to supply CAPCOM process heat demand is:

$$0.251\frac{g\ CO_2eq}{MJ_{fibers\&shells}} \times \frac{MJ_{fibers\&shells}}{0.85\ MJ_h} \times 211.6\ \frac{kJ_h}{MJ_{pellet}} \times \frac{1\ MJ}{1000\ kJ} = 0.062\ \frac{g\ CO_2eq}{MJ_{pellet}}$$

Total emissions associated with energy demand of CAPCOM bagasse pellet production is: 0.255 $gCO_2eq/MJ_{\text{pellet}}$.

Diesel

Additionally, diesel is required for bulldozers for feeding of feedstock and trucks for ash removal. The demand is typically 0.0024 MJ diesel per MJ pellet. The emissions associated with diesel use is:

$$0.0024\frac{MJ_{diesel}}{MJ_{pellet}} \times 95.1\frac{g\ CO_2eq}{MJ_{diesel}} = 0.228\frac{g\ CO_2eq}{MJ_{pellet}}$$

Credit for returned nutrients

GHG emissions savings from returned nutrients can be calculated as:

$$2.40 \times 10^{-3} \frac{kg\ KCl}{MJ_{pellet}} \times \frac{94.2\ kg\ K_2O}{74.5\ kg\ KCl} \times \frac{1}{2} \times 416.7 \frac{g\ CO_2eq}{kg\ K_2O} = 0.633 \frac{g\ CO_2eq}{MJ_{pellet}}$$

$$6.62 \times 10^{-5} \frac{kg\ P}{MJ_{pellet}} \times \frac{141.9\ kg\ P_2O_5}{31\ kg\ P} \times \frac{1}{2} \times 541.7 \frac{g\ CO_2eq}{kg\ P_2O_5} = 0.082 \frac{g\ CO_2eq}{MJ_{pellet}}$$

Table 34 GHG emissions from processing of CAPCOM EFB pellets

	GHG emissions, gCO_2eq/MJ_{pellet}
Heat and Electricity	0.255
Diesel	0.228
Credit for returned nutrients	-0.715
Total	-0.232

6.4.2 Transportation to the Netherlands

6.4.2.1 Bagasse pellets and SCT pellets

Transport emissions can be divided into 3 parts:

- Road transport of pellets from the mill to the port in Brazil
- Transoceanic transport of pellets from port in Brazil to the port in Netherlands
- Barge transport from port to the power plant in the Netherlands

Road transport of pellets from the mill to the port in Brazil

The transportation demand per MJ bagasse pellet is : 0.023 tkm/MJ pellet

The transportation demand per MJ SCT pellet is : 0.025 tkm/MJ pellet

Table 35 GHG emissions for road transport from the mill to the port - Bagasse

	Amount	*Unit*	*Emission factor*	*Unit*	*GHG emissions*	
CH_4	7.87×10^{-5}	g/MJ_{pellet}	25	gCO_2/gCH_4	0.0020	gCO_2eq/MJ_{pellet}
N_2O	3.47×10^{-5}	g/MJ_{pellet}	298	gCO_2/gN_2O	0.0103	gCO_2eq/MJ_{pellet}
Diesel	0.0188	MJ_{diesel}/MJ_{pellet}	95.1	gCO_2/MJ_{diesel}	1.7853	gCO_2eq/MJ_{pellet}
Total					1.7976	gCO_2eq/MJ_{pellet}

Table 36 GHG emissions for road transport from the mill to the port - SCT

	Amount	*Unit*	*Emission factor*	*Unit*	*GHG emissions*	
CH_4	8.31×10^{-5}	g/MJ_{pellet}	25	gCO_2/gCH_4	0.0021	gCO_2eq/MJ_{pellet}
N_2O	3.67×10^{-5}	g/MJ_{pellet}	298	gCO_2/gN_2O	0.0109	gCO_2eq/MJ_{pellet}
Diesel	0.020	MJ_{diesel}/MJ_{pellet}	95.1	gCO_2/MJ_{diesel}	1.8855	gCO_2eq/MJ_{pellet}
Total					1.8985	gCO_2eq/MJ_{pellet}

Transoceanic transport of pellets from port in Brazil to the port in Netherlands

The transportation demand per MJ bagasse pellet is : 0.581 tkm/MJ pellet

The transportation demand per MJ SCT pellet is : 0.614 tkm/MJ pellet

Table 37 GHG emissions from transoceanic transport - Bagasse

	Amount	*Unit*	*Emission factor*	*Unit*	*GHG emissions*	
Heavy fuel oil (HFO)	0.038	MJ_{HFO}/MJ_{pellet}	94.2	gCO_2/MJ_{HFO}	3.594	gCO_2eq/MJ_{pellet}

Table 38 GHG emissions from transoceanic transport - SCT

	Amount	*Unit*	*Emission factor*	*Unit*	*GHG emissions*	
Heavy fuel oil (HFO)	0.040	MJ_{HFO}/MJ_{pellet}	94.2	gCO_2/MJ_{HFO}	3.791	gCO_2eq/MJ_{pellet}

Barge transport from port to the power plant in the Netherlands
The transportation demand per MJ bagasse and SCT pellet is : 0.003 tkm/MJ pellet

Table 39 GHG emissions from barge transport to the power plant – Bagasse & SCT

	Amount	*Unit*	*Emission factor*	*Unit*	*GHG emissions*	
CH_4	$2.79x10^{-4}$	g/MJ_{pellet}	25	gCO_2/gCH_4	0.0070	gCO_2eq/MJ_{pellet}
N_2O	$1.20x10^{-6}$	g/MJ_{pellet}	298	gCO_2/gN_2O	0.0004	gCO_2eq/MJ_{pellet}
Diesel	$9.72x10^{-4}$	MJ_{diesel}/MJ_{pellet}	95.1	gCO_2/MJ_{diesel}	0.0924	gCO_2eq/MJ_{pellet}
Total					0.0998	gCO_2eq/MJ_{pellet}

Accordingly the total emissions from the transportation of bagasse and SCT pellets can be calculated as:

Table 40 GHG emissions from transportation of CAPCOM bagasse pellets

	GHG emissions, gCO_2eq/MJ_{pellet}
Road transport	1.7976
Transoceanic transport	3.5940
Barge transport	0.0998
Total	5.4914

Table 41 GHG emissions from transportation of CAPCOM SCT pellets

	GHG emissions, gCO_2eq/MJ_{pellet}
Road transport	1.8985
Transoceanic transport	3.7915
Barge transport	0.0998
Total	5.7897

6.4.2.2 EFB pellets

Transport emissions can be divided into 3 parts:

- Rail transportation of pellets from the mill to the port in Colombia
- Transoceanic transportation from port in Colombia to the port in Netherlands
- Barge transportation from port to the power plant in the Netherlands

Road transport of pellets from the mill to the port in Colombia
The transportation demand per MJ EFB pellet is : 0.006 tkm/MJ pellet

Table 42 GHG emissions for rail transport from the mill to the port

	Amount	*Unit*	*Emission factor*	*Unit*	*GHG emissions*	
CH_4	$2.92x10^{-5}$	g/MJ_{pellet}	25	gCO_2/gCH_4	0.0007	gCO_2eq/MJ_{pellet}
N_2O	$5.85x10^{-6}$	g/MJ_{pellet}	298	gCO_2/gN_2O	0.0017	gCO_2eq/MJ_{pellet}
Diesel	$1.47x10^{-3}$	MJ_{diesel}/MJ_{pellet}	95.1	gCO_2/MJ_{diesel}	0.1402	gCO_2eq/MJ_{pellet}
Total					0.1426	gCO_2eq/MJ_{pellet}

Transoceanic transport of pellets from port in Brazil to the port in Netherlands
The transportation demand per MJ EFB pellet is : 0.494 tkm/MJ pellet

Table 43 GHG emissions from transoceanic transport - Bagasse

	Amount	*Unit*	*Emission factor*	*Unit*	*GHG emissions*	
Heavy fuel oil (HFO)	0.032	MJ_{HFO}/MJ_{pellet}	94.2	gCO_2/MJ_{HFO}	3.061	gCO_2eq/MJ_{pellet}

Barge transport from port to the power plant in the Netherlands
The transportation demand per MJ EFB pellet is : 0.003 tkm/MJ pellet

Table 44 GHG emissions from barge transport to the power plant

	Amount	*Unit*	*Emission factor*	*Unit*	*GHG emissions*	
CH_4	2.79×10^{-4}	g/MJ_{pellet}	25	gCO_2/gCH_4	0.0070	gCO_2eq/MJ_{pellet}
N_2O	1.20×10^{-6}	g/MJ_{pellet}	298	gCO_2/gN_2O	0.0004	gCO_2eq/MJ_{pellet}
Diesel	9.72×10^{-4}	MJ_{diesel}/MJ_{pellet}	95.1	gCO_2/MJ_{diesel}	0.0924	gCO_2eq/MJ_{pellet}
Total					0.0998	gCO_2eq/MJ_{pellet}

Accordingly the total emissions from the transportation of EFB pellets can be calculated as:

Table 45 GHG emissions from transportation of CAPCOM EFB pellets

	GHG emissions, gCO_2eq/MJ_{pellet}
Rail transport	0.1426
Transoceanic transport	3.0608
Barge transport	0.0998
Total	3.3032

6.4.3 Overview and comparison with wood pellets from North America

Overview of GHG emissions of CAPCOM pellets before end use
Before end use, the GHG emissions associated with 1 MJ CAPCOM pellets are calculated as:

Table 46 GHG emissions from the production of CAPCOM pellets

	Bagasse pellets GHG emissions, gCO_2eq/MJ_{pellet}	*SCT pellets GHG emissions,* gCO_2eq/MJ_{pellet}	*EFB pellets GHG emissions,* gCO_2eq/MJ_{pellet}
Collection	0	0.411	0
Processing to pellets	0.328	0.389	0.483
Credit for returned nutrients	0	-0.153	-0.715
Road transport	1.7976	1.8985	0
Rail transport	0	0	0.1426
Transoceanic transport	3.5940	3.7915	3.0608
Barge transport	0.0998	0.0998	0.0998
Total	5.82	6.44	3.07

The breakdown of the impacts are provided in Figure 9:

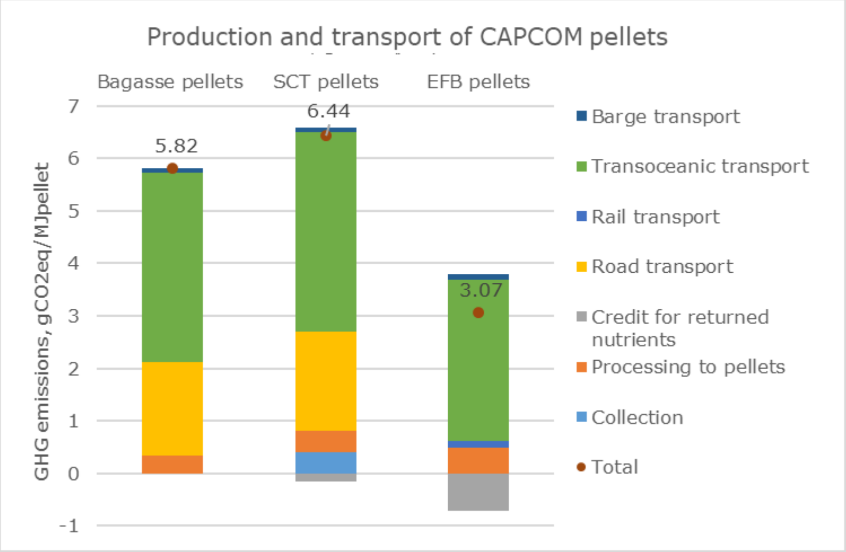

Figure 9 ***Breakdown of the GHG emissions from the production and transport of CAPCOM pellets***

GHG emissions of wood pellets from North America

GHG emissions of wood pellets from North America are used as a comparison. There are different sources that can be used for wood pellet production. In REDII default values are provided for wood pellets from forestry residues, short rotation coppice (eucalyptus and poplar), stemwood and wood industry residues. Forestry residues and wood industry residues (sawdust) are selected as suitable feedstock for wood pellets for comparison with CAPCOM pellets. There are three sets of results provided in REDII for the pathways wood pellets from forest residues and wood industry residues (cases 1, 2a and 3a). The difference is in the fuel source used in the pellet mill. The case 3a is selected where the process heat and electricity in the pellet mill is provided by wood chips CHP. The other options consider NG boiler (case 1) and wood chips boiler (case 2a). REDII default values provided for “Wood pellets from forest residues (case 3a)” and “Wood pellets from wood industry residues (case 3a)” are used for comparison with CAPCOM pellets. Also for each there is a choice of location/transportation distance. The distance tag of >10 000 km is considered which provides default transportation distances considering Western Canada as geographical origin. No default values are provided in REDII for sourcing origin of US, this is additionally modelled using the transportation distances described below.

Similar to the CAPCOM pellet pathways, there are no cultivation emissions and the calculation is simplified into:

$$E = e_p + e_{td} + e_u$$

The processing consists of:

- Forest residues collection and chipping (not applicable to wood industry residue pathway)
- Pellet production

The transportation consists of:

- Transport of wood chips
- Transport of wood pellets by train to port
- Transoceanic transport of wood pellets

The transportation distances and modes considered for these are summarized in Table 47. Barge transport emissions is also included to be consistent with the transportation of CAPCOM pellets.

Table 47 ***Transportation scheme for wood pellet pathways***

Distance tag	**Representative geographic origin**	**Typical distances (km)**			
		Truck (chips)	Train (pellets)	Bulk carrier (pellets)	Barge
> 10000 km	Western Canada	100	750	16500	50
	US	100	750	7300	50

Before end use, the GHG emissions associated with 1 MJ wood pellets are calculated as:

Table 48 ***GHG emissions from the production of wood pellets from North America***[23]

	GHG emissions of Wood pellets from forest residues, gCO_2eq/MJ_{pellet}		*GHG emissions of Wood pellets from industry residues,* gCO_2eq/MJ_{pellet}	
	From Canada	*From US*	*From Canada*	*From US*
Collection and chipping	2.4338	2.4338	0	0
Processing to pellets	0.3978	0.3978	0.2665	0.2665
Road transport	1.3717	1.3717	0.9071	0.9071
Rail transport	1.2836	1.2836	1.2836	1.2836
Transoceanic transport	7.1536	3.1649	7.1536	3.1649
Barge transport	0.0998	0.0998	0.0998	0.0998
Total	12.74	8.75	9.71	5.72

The results show that CAPCOM pellets produced in Colombia or Brazil and transported to the Netherlands
have a similar or better GHG performance compared to the wood pellets sourced from North America using forestry or industry residues as feedstock.

6.4.4 Electricity production from CAPCOM pellets and comparison with fossil fuel reference

Electricity production from CAPCOM pellets

Emissions from the fuel in use for electricity production is calculated considering non-CO_2 emissions from co-combustion of CAPCOM pellets and from the electricity used for pulverizing.

Table 49 ***GHG emissions from electricity end use***

	Amount	*Unit*	*Emission factor*	*Unit*	*GHG emissions*	
CH_4	0.0009	g/MJ pellet	25	gCO_2/gCH_4	0.0225	gCO_2eq/MJ_{pellet}
N_2O	0.0014	g/MJ pellet	298	gCO_2/gN_2O	0.4172	gCO_2eq/MJ_{pellet}
Electricity	0.0094	MJ_e/MJ_{pellet}	164	gCO_2/MJ_e	1.5537	gCO_2eq/MJ_{pellet}
Total					1.9934	gCO_2eq/MJ_{pellet}

The overall GHG emissions from bagasse pellet ($E = e_p + e_{td} + e_u$) is calculated by adding this e_u value to the GHG emissions calculated in Table 46 which provide sum of processing and transportation ($e_p + e_{td}$).

The emissions per MJ pellet then need to be converted to the emissions per MJ electricity using 41% efficiency (η_{el}). The emissions from electricity (final energy) production is calculated with the formula :

$$EC_{el} = \frac{E}{\eta_{el}}$$

Table 50 GHG emissions of CAPCOM pellets per MJ electricity

	Bagasse pellets GHG emissions	*SCT pellets GHG emissions*	*EFB pellets GHG emissions*
Processing + Transport (e_p + e_{td}), gCO_2eq/MJ_{pellet}	5.8194	6.4367	3.0712
Electricity production (e_u), gCO_2eq/MJ_{pellet}	1.9934	1.9934	1.9934
Overall emissions, gCO_2eq/MJ_{pellet}	7.8128	8.4301	5.0646
Overall emissions, gCO_2eq/MJ_e	19.05	20.56	12.35

Comparison with fossil fuel reference

GHG emissions savings from electricity being generated compared to fossil fuels can be calculated with the following formula:

$$SAVING = (EC_{F(el)} - EC_{B(el)})/EC_{F\,(el)}$$

Total emissions from the fossil fuel comparator for electricity, $EC_{F(el)}$, is considered by REDII to be 183 g CO_2eq/MJ electricity. The $EC_{B(el)}$, total emissions from the electricity generated by biomass fuels, is calculated above in Table 50. Accordingly the GHG emissions savings can be calculated as:

Table 51 GHG emissions savings of CAPCOM pellets for electricity production

	Bagasse pellets	*SCT pellets*	*EFB pellets*
GHG emissions savings	89.6%	88.8%	93.2%

RED II requires at least 70 % GHG emissions savings for electricity, heating and cooling production from biomass fuels used in installations starting operation from 1 January 2021 until 31 December 2025, and 80 % for installations starting operation from 1 January 2026.

Therefore, the GHG savings achieved with CAPCOM pellets comply with the REDII criteria, also considering installations to go into operation after 2026.

6.4.5 Ethanol production from CAPCOM pellets and comparison with fossil fuel reference

Using results reported by Maga *et al.* for unit processes following P3 gives total impact of conversion of pre-treated bagasse and SCT to ethanol as $9.5\text{x}10^{-2}$ $kgCO_2eq$/L ethanol. The breakdown provided in the study is shown in Table 52.

Table 52 Breakdown of GHG emissions from conversion of treated bagasse and SCT to ethanol

Process	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Climate change, kg CO_2eq/L	2.8E-02	2.9E-03	3.9E-02	5.1E-03	0	0	2.0E-02	1.4E-05

(3) Enzyme production (4) Enzymatic Hydrolysis (5) Inoculum preparation (6) Ethanol fermentation SHF (7) Distillation and dehydration (8) Wastewater treatment (9) Steam and power generation (10) Absorption chiller

The LHV of ethanol is 21.3 MJ/L, the GHG impact of ethanol calculation then be converted as:

$$9.5 \times 10^{-2}\,\frac{kgCO_2eq}{L_{ethanol}} \times \frac{L_{ethanol}}{21.3\,MJ_{ethanol}} \times \frac{1000\,g}{1\,kg} = 4.47\,\frac{gCO_2eq}{MJ_{ethanol}}$$

For converting the GHG emissions from processing and transportation of CAPCOM pellets calculated in Table 46 per MJ pellet to per MJ ethanol following factors are calculated:

For bagasse:

$$0.217\,\frac{kg_{ethanol}}{kg_{bagasse}} \times \frac{kg_{bagasse}}{19.2MJ_{bagasse}} \times 26.8\,\frac{MJ_{ethanol}}{kg_{ethanol}} = 0.303\,\frac{MJ_{ethanol}}{MJ_{bagasse}}$$

For SCT:

$$0.217\frac{kg_{ethanol}}{kg_{SCT}}\times\frac{kg_{SCT}}{18.2MJ_{SCT}}\times 26.8\frac{MJ_{ethanol}}{kg_{ethanol}}=0.319\frac{MJ_{ethanol}}{MJ_{SCT}}$$

For EFB:

$$0.245\frac{kg_{ethanol}}{kg_{EFB}}\times\frac{kg_{EFB}}{19MJ_{EFB}}\times 26.8\frac{MJ_{ethanol}}{kg_{ethanol}}=0.345\frac{MJ_{ethanol}}{MJ_{EFB}}$$

Furthermore, transportation of ethanol to depot and then the transportation of ethanol to filling stations need to be added. For the default value for transport and distribution of ethanol provided by REDII of 1.6 gCO_2eq/MJ ethanol is used. The overall GHG emissions are accordingly calculated in Table 53.

Table 53 GHG emissions of CAPCOM pellets per MJ ethanol

	Bagasse pellets GHG emissions	*SCT pellets GHG emissions*	*EFB pellets GHG emissions*
Processing and transport of CAPCOM pellets, gCO_2eq/MJ_{pellet}	5.82	6.44	3.07
Processing and transport of CAPCOM pellets, $gCO_2eq/MJ_{ethanol}$	19.20	20.18	8.90
Ethanol production, $gCO_2eq/MJ_{ethanol}$	4.47	4.47	4.47
Transport and distribution of ethanol, $gCO_2eq/MJ_{ethanol}$	1.60	1.60	1.60
Overall emissions, $gCO_2eq/MJ_{ethanol}$	25.27	26.25	14.97

Comparison with fossil fuel reference

GHG emissions savings from ethanol being generated compared to fossil fuels can be calculated with the following formula:

$SAVING = (EC_{F(t)} - EC_B)/EC_{F(t)}$

Total emissions from the fossil fuel comparator for transport, $EC_{F(t)}$, is considered by REDII to be 94 g CO_2eq/MJ. The EC_B, total emissions from the bioethanol, is calculated above in Table 53. Accordingly the GHG emissions savings can be calculated as:

Table 54 GHG emissions savings of CAPCOM pellets for ethanol production

	Bagasse pellets	*SCT pellets*	*EFB pellets*
GHG emissions savings	73.1%	72.1%	84.0%

RED II requires at least 65 % GHG emissions savings for biofuels consumed in the transport sector produced in installations starting operation from 1 January 2021. Therefore, the GHG savings achieved with CAPCOM pellets comply with the REDII criteria.

Comparison with other biofuel pathways

Default life cycle GHG emissions are provided in RED II for example for ethanol produced from sugarcane, sugar beet, other cereals and wheat straw ethanol. The values for ethanol produced from corn and other cereals depend on the source of process fuel used (either natural gas, lignite or forest residues). The values for sugar beet ethanol depend on the process fuel (either natural gas and lignite), use of boiler or CHP plant and whether biogas is produced from slop. The values are provided in Table 55. It can be seen that ethanol produced from CAPCOM pellets from bagasse and SCT perform similar to ethanol produced from crops and perform worse than wheat straw ethanol. For EFB pellet based ethanol similar performance to wheat straw ethanol is seen.

Table 55 GHG emissions of alternative bioethanol pathways

	GHG emissions, $gCO_2eq/MJ_{ethanol}$
Sugar beet ethanol	22.5 – 50.2
Corn ethanol	30.3 – 67.8
Other cereals ethanol	31.4 – 71.7
Sugar cane ethanol	28.6
Wheat straw ethanol	15.7

6.5 Interpretation and discussion

The results show that CAPCOM pellets produced and shipped to the Netherlands for electricity or ethanol production have a favourable GHG emissions performance. They are found to comfortably comply with the REDII criteria with respect to production from fossil fuels. They are also found to have a comparable GHG performance to the wood pellets from forestry or industry residues sourced from North America.

The results and comparisons are sensitive to variation in the following parameters:

- Source of energy used for CAPCOM processes
- Nutrient recovery for SCT and EFB pellet production
- Road transport distance in Brazil
- Mode of transport and distance in Colombia
- End use electrical efficiency
- End use ethanol yield

6.5.1 Sensitivity analysis

6.5.1.1 Pellet production

Source of energy used for CAPCOM processes

For production of pellets from bagasse and SCT, surplus electricity and surplus bagasse available from the sugarcane mill are considered to supply the electricity and heat demand of CAPCOM processes. For EFB pellet production, surplus electricity and surplus of mesocarp fibre and palm kernel shells available in palm oil mill are considered to cover the electricity and heat demand of CAPCOM processes.

A sensitivity analysis is performed to assess the impact if all the energy demand would need to be supplied externally. This is not expected to be necessary as investigated in section 5.3. For electricity, supply from the grid is considered where for Brazil the emission factor is 60 gCO_2eq/MJ_e[37] and for Colombia it is 74.7 gCO_2eq/MJ_e[38]. For heat it is considered to be supplied with natural gas boiler with 90% thermal efficiency. Emission factor for provision of natural gas is 66 gCO_2eq/MJ[23].

This change is seen to have a very big impact. The overall GHG emissions of CAPCOM pellets would rise to above 20 gCO_2eq/MJ_{pellet}. This would result in them no longer able to meet the GHG emissions savings requirements of REDII. This shows the importance of ensuring supply of energy of pellet production through mills own surplus electricity and biomass residues.

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[37] Ecoinvent 3.6, Electricity, high voltage {BR-South-eastern grid}| market for electricity, high voltage | APOS, U.

[38] Ecoinvent 3.6, Electricity, high voltage {CO}| market for electricity, high voltage | APOS, U.

Table 56 ***GHG emissions from processing of CAPCOM pellets with internal supply vs. external supply***

	GHG emissions internal energy supply, gCO_2eq/MJ_{pellet}	*GHG emissions external energy supply,* gCO_2eq/MJ_{pellet}
Bagasse		
Electricity	0.05	2.10
Heat	0.05	12.11
Total	0.10	14.21
SCT		
Electricity	0.08	3.44
Heat	0.08	19.31
Total	0.16	22.75
EFB		
Electricity	0.19	5.79
Heat	0.06	15.52
Total	0.25	21.31

Nutrient recovery for SCT and EFB pellet production

There is uncertainty in the amount of nutrients that can be extracted from SCT and EFB and can be returned to field thereby displacing artificial fertilizer input. Therefore a sensitivity analysis is conducted on its ±10% variation.

Table 57 ***Sensitivity on credit for returned nutrients***

Credit for returned nutrients, gCO_2eq/MJ_{pellet}	-10%	Baseline	+10%
CAPCOM SCT	-0.138	-0.153	-0.168
CAPCOM EFB	-0.644	-0.715	-0.787

This results in 0.2% and 2.3% variation in overall GHG emissions of pellets before end use for SCT and EFB pellets respectively. This means the overall emission results are less sensitive to variation in amount of returned nutrients.

6.5.1.2 Pellet transport

Road transport distance in Brazil

It is considered that the road transportation of bagasse and SCT pellets from the mill to the harbour will take place over a distance of 400 km. This is an approximation and could vary. REDII default value for bagasse pellets transported over 10000 km is calculated considering for road transport a transportation distance of 700 km instead of 400 km. The impact of the ±300 km variation in distance is shown in Table 58. Having a longer distance of 700 km will result in 22% higher overall GHG emissions of pellets before end use. Still, use of these pellets for electricity production results in about 87% GHG emissions savings with respect to fossil fuel comparator.

Table 58 ***Sensitivity of results on the road transport distance in Brazil***

	Road transport distance, km		
	100	*400*	*700*
Bagasse			
Road transport, gCO_2eq/MJ_{pellet}	0.45	1.80	3.15
Overall emissions, gCO_2eq/MJ_{pellet}	4.47	5.82	7.17
SCT			
Road transport, gCO_2eq/MJ_{pellet}	0.47	1.90	3.32
Overall emissions, gCO_2eq/MJ_{pellet}	5.01	6.44	7.86

Mode of transport and distance in Colombia

It is considered that the transportation of EFB pellets from the mill to the harbour will take place by rail over a distance of 100 km. This is considering only supply from the Magdalena region.

However, this is representative about 15% of palm oil mills in Colombia and the majority of production takes place in Eastern and Central regions of Colombia.[39] Taking Santander in Central region as representative would give 600 km for average transportation distance to the harbour. The railway goes until Chiriguana[40]. This means transportation from the mill to the harbour takes place 350 km by truck and 250 km by rail. The impact of this variation is shown in Table 59. Having a longer distance results in about 60% higher overall GHG emissions of EFB pellets before end use.

Table 59 Sensitivity of results on the road transport distance and mode in Colombia

GHG emissions, gCO_2eq/MJ_{pellet}	*Baseline (100 km rail)*	*Longer distance (250 km rail + 350 km truck)*
Rail transport	0.14	0.36
Truck transport	0	1.60
Overall emissions	3.07	4.88

6.5.1.3 Electricity production – Electrical efficiency

In this study, electrical efficiency of 41% was used. The evaluation with respect to fossil fuel comparator can differ significantly if the electrical efficiency is varied. To show the impact of this variation the results are shown in Table 60 also for 30% and 50% electrical efficiency and the associated GHG savings.

Table 60 Sensitivity of results on the electrical efficiency of final conversion

	Electrical Efficiency		
	30%	*41%*	*50%*
Bagasse			
GHG emissions, gCO_2eq/MJ_e	26.04	19.05	15.63
GHG emissions savings, %	85.8%	89.6%	91.5%
SCT			
GHG emissions, gCO_2eq/MJ_e	28.1	20.56	16.86
GHG emissions savings, %	84.6%	88.8%	90.8%
EFB			
GHG emissions, gCO_2eq/MJ_e	16.88	12.35	10.13
GHG emissions savings, %	90.8%	93.2%	94.5%

It is seen that although CAPCOM pellets still comply with the REDII criteria, it is important to use CAPCOM pellets in efficient, large scale installations.

6.5.1.4 Ethanol production – Ethanol yield

Ethanol yield for CAPCOM pellets are calculated using literature information of 80% hydrolysis yield and yields of 0.45 and 0.35 g/g of ethanol from glucose and xylose, respectively. A sensitivity analysis is carried out considering overall ethanol yield variation of ±10%. The impact of this variation on the overall GHG emissions and the associated GHG emissions savings are shown in Table 61.

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[39] Statista, Distribution of palm oil production in Colombia in 2018, by region, Available from: www.statista.com

[40] Fenoco, https://www.fenoco.com.co/index.php/railway-map

Table 61 Sensitivity of results on the ethanol yield

	Ethanol yield		
	-10%	*Baseline*	*+10%*
Bagasse			
GHG emissions, $gCO_2eq/MJ_{ethanol}$	27.41	25.27	23.53
GHG emissions savings, %	70.8%	73.1%	75.0%
SCT			
GHG emissions, $gCO_2eq/MJ_{ethanol}$	28.49	26.25	24.41
GHG emissions savings, %	69.7%	72.1%	74.0%
EFB			
GHG emissions, $gCO_2eq/MJ_{ethanol}$	15.96	14.97	14.16
GHG emissions savings, %	83.0%	84.0%	84.9%

It is seen that even with the 10% decrease, GHG emissions saving criteria of RED II for biofuels of at least 65 % can be met.

6.5.2 Consequences of removing residues from current systems

REDII considers that residues have zero life-cycle greenhouse gas emissions up to the process of collection. EFB, sugarcane trash and bagasse are all considered to be residues by REDII. Thereby, no emissions are allocated to their production.

Sugarcane trash is left on the field. It can be considered burden free until point of collection if the collected amount doesn't exceed sustainable harvesting level. Due to phasing out of burned harvesting practice, there is currently growing layers of it on land. Accordingly, the use of trash is not expected to be an issue and can even be beneficial (e.g. preventing rotting and fungus, insects, snakes, etc.). EFB can also be considered burden free until point of collection as it is currently highly unutilized. It currently mostly finds use as compost. CAPCOM-NL considers the washing liquid from extraction of sugarcane trash and EFB, that contains valuable minerals, to be brought to the field. This would allow compensating for the residues removed from the system.

The surplus bagasse on the other hand is most often utilized. It is sold as a fuel or converted to electricity in the mill and supplied to the grid. This means removing the bagasse from Brazil for supply to the Netherlands can have consequences with environmental implications. In Brazil small changes in demand for electricity will not influence the capacity of electricity production by hydropower. Accordingly, source used for marginal electricity production is relevant. Natural gas is seen to be predominantly used in power plants in Brazil for this {Seabra, 2011 #77}.**Fout! Bladwijzer niet gedefinieerd.** Therefore, it will be likely that exporting bagasse pellets would result in additional natural gas consumption in Brazil to deliver the existing energy needs covered by electricity supplied through surplus bagasse in Brazil. Accordingly, Maga *et al.* {Maga, 2019 #81} considered allocation needs to be applied between bagasse and sugar produced in the mill. A monetary allocation for bagasse of 103.3 R$/t of bagasse is applied based on the opportunity cost of electricity generation. Taking a price for sugar produced of 1000 R$/t, gives an allocation factor of 9% to bagasse of the burdens of sugarcane production and transport {Maga, 2019 #81}. To estimate the environmental consequences more accurately, it is important to understand how much surplus bagasse is currently produced and what share of this is currently actually utilized as it is known that in some locations surplus bagasse is not completely utilized.

6.5.3 Options to free up additional bagasse

Two options exist for freeing up bagasse from sugar mills. These are implementation of CHP improvements at the sugar mill and co-feeding of straw to supply energy requirements. The bagasse attained through these approaches can be considered to be available with no indirect effects (meaning burden free).

Due to readily available fuel source of bagasse, sugar mill thermal systems remained inefficient and did not consider technological update. With increased efficiency, less bagasse would be needed to supply the internal energy demands and this would free up additional bagasse. CHP efficiency improvement require investment in installations.

The most common modifications in the cogeneration units include installation of high-efficiency boilers, replacement of steam-driven mechanical drives with electric drives and upgraded steam turbines [47]. Some mills already optimize the use of bagasse for surplus electricity production. A concern for surplus electricity production is that in Brazil, electricity is mainly supplied through hydropower which is more economical than generating it from biomass. This could deter investments in increasing energy efficiency in the mills because of low returns. However, during the country's recent droughts, power production fuelled by bagasse had a growing contribution to overall power generation as the hydroelectric power generation was reduced.[41] The surplus bagasse can also be used for pellet production.

The second opportunity to leverage additional bagasse is feeding sugarcane trash as supplementary fuel to bagasse. This can replace a share of the used bagasse. The amount of sugarcane trash that can be co-fed with bagasse would be limited to the equipment capabilities. This is usually due to the higher chlorine and potassium content in sugarcane trash causing technical problems in the boiler such as corrosion, deposits on hot surfaces and the slagging of ashes [48]. These could be overcome by washing the trash which is carried out in CAPCOM process. RWE sees potential in sugarcane trash to replace bagasse up to 30% meaning the possibility of additional 30% bagasse can be freed up. This is of interest seen in recent literature [13, 14].

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[41] Agora Energiewende & Instituto E+ Diálogos Energéticos (2019): Report on the Brazilian Power System, (agora-energiewende.de)

7 Conclusions

Three pathways to produce CAPCOM were selected:

4. Sugarcane bagasse -> CAPCOM
5. Sugarcane trash -> CAPCOM
6. Empty fruit bunch -> CAPCOM

Also 2 end uses of CAPCOM's are considered for analysis of full chain:

3. CAPCOM -> Electricity
4. CAPCOM -> Ethanol

Using the mass and energy balances for the production of the CAPCOMs (provided in Deliverable 3) from process design, techno-economic analysis (TEA) and life cycle analysis (LCA) were performed.

7.1 Conclusions from Techno Economic Assessment (TEA)

Pellet production and transport to a powerplant nearby Rotterdam harbour in Netherlands result in costs of 6.3 €/GJ for pellets made from gain sugar trash in Brazil, 5.1 €/GJ for pellets made from EFB in Colombia and 6.0 €/GJ for pellets made from bagasse in Brazil. Values are based on the LHV and include transport from a location not too far from a harbour in the producing countries. Costs can be higher if feedstock prices are higher and will probably be higher for transport during market (storage) development (the calculated costs fits better with regular transport and large volumes).
If the screw press can reach a low enough water content in case of EFB, the pre-dryer and first condenser can be skipped, reducing production and transport costs with 5% to 4.9 €/GJ.
Under the CO_2 trading system in Europe (EU-ETS) those pellets are competitive with coal in power plants near Rotterdam with a fuel price of 6.1 €/GJ (including CO_2-costs of 44 €/ton; the EU-ETS price in March 2021). The EU-ETS price is expected to drop in the near future, but may well rise in the long term as more stringent CO_2 emissions will apply.
The calculated values naturally have the necessary margins of uncertainty, both in current value and in future developments. This TEA does has not investigated or optimized what the best storage method would be. This depends on the number of producers and the port facilities in the country of origin and in Rotterdam.
The TEA showed that the investments can be an obstacle, but only have a limited influence on the ultimate production costs. Domestic transport in the producing countries and sea transport are more important. If domestic transport distances become long, for instance 800 km, it is much better to use rail transport or inland shipping instead of truck transport.
Because the dry weight of the feedstock directly related to the weight of the pellets (with some material losses), feedstock cost have a large effect on the pellet production costs.
Two remarkable things emerge from the analysis. The use of own residual flows for the production of heat and electricity is important for limiting production costs. In addition, the return (recycling) of the wash water from trash and EFB is important for limiting the loss of fertilizers and minerals. This recycling also has a visible financial advantage.

7.2 Conclusions from Life Cycle Analysis (LCA)

In LCA, the overall GHG impacts of three possible chains of CAPCOM were assessed. Cradle to gate impacts (from production of 1 MJ pellet) as well as cradle to grid/wheel impacts were studied considering two end products of electricity and ethanol from pellets. REDII GHG emissions accounting methodology was followed. The overall GHG emissions of the CAPCOM pellets were calculated to be 5.82, 6.44 and 3.07 gCO_2eq/MJ_{pellet} for bagasse, SCT and EFB respectively. The lower emissions attained for EFB is due to the high impact (-0.7 gCO_2eq/MJ_{pellet}) seen from the credits attained from returned nutrients and having rail transport instead of road transport of pellets to the port. For all three pathways transoceanic transportation has also significant contribution (above 3 gCO_2eq/MJ_{pellet}). Comparison was made with wood pellets sourced from North America which is calculated to have overall GHG emissions in the range of 5.72-12.74 gCO_2eq/MJ_{pellet} considering forest residues and industry residues as feedstock and Canada and US as production locations. It is seen that CAPCOM pellets can perform similar to (and in some cases better than) wood pellets.

When CAPCOM pellets are converted to electricity, the GHG emissions per MJ electricity were calculated as 19.05, 20.56 and 12.35 gCO_2eq/MJ_e for bagasse, SCT and EFB respectively. This resulted in GHG emissions savings of 89.6%, 88.8% and 93.2% for bagasse, SCT and EFB respectively with respect to fossil fuel comparator for electricity. Evaluation of the GHG emissions for production of ethanol gave 25.27, 26.25 and 14.97 $gCO_2eq/MJ_{ethanol}$ for bagasse, SCT and EFB respectively. This resulted in GHG emissions savings of 73.1%, 72.1% and 84.0% for bagasse, SCT and EFB respectively with respect to fossil fuel comparator for transport. It was also seen that ethanol produced using CAPCOM pellets from bagasse and SCT perform similar to ethanol produced from crops and perform worse than wheat straw ethanol. For EFB pellet based ethanol similar performance to wheat straw ethanol is seen.

The GHG emissions accounting methodology described in RED II considers residues to be free of burdens until point of collection. This is considered suitable for EFB and SCT especially considering the possibility to return nutrients in the CAPCOM process. In case of bagasse, the surplus bagasse is most often utilized (electricity to grid) which means removing the bagasse from Brazil for supply to Netherlands can have consequences with environmental implications. Two approaches are accordingly described for freeing up bagasse from sugar mills which can be considered available burden free. These are implementation of CHP improvements at the sugar mill and co-feeding of straw to supply energy requirements.

In summary, this research shows that CAPCOM pellets produced in Brazil or Colombia and supplied to the Netherlands show a good potential by meeting the GHG emissions savings criteria (for both electricity and biofuel) and offering an alternative for wood pellets sourced from the North America. CAPCOM pellets can accordingly make an important contribution to meeting the growing demand for biomass pellets for renewable electricity as well as for advanced biofuels. Furthermore, this mobilization of residues and setting up a supply chain for pellets would be beneficial for stimulating local development and economic activity.

8 Literature

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Annex A. Life cycle inventory tables for CAPCOM pellets production

These supplementary tables provide life cycle inventory tables for the investigated CAPCOM pellet production processes. They are presented per functional unit of 1 MJ CAPCOM pellet.

Sugarcane Trash

	Input/Output	*Amount*	*Unit /MJ pellet*
Sugarcane trash (SCT)	Input	1.32	MJ
Size reduction step			
Electricity	Input	3.08	kJ
CC SMB extraction			
Electricity	Input	9.03	kJ
Water	Input	0.31	kg
Waste water	Output	0.19	kg
Water	Output	0.18	kg
Organic material	Output	6.88E-03	kg
KCl	Output	5.50E-04	kg
Magnesium	Output	4.71E-05	kg
Calcium	Output	6.54E-07	kg
Phosphorus	Output	6.36E-08	kg
Sulfur	Output	8.83E-09	kg
Iron	Output	5.28E-09	kg
Screw press			
Waste water	Output	5.66E-02	kg
Water	Output	5.52E-02	kg
Organic material	Output	1.24E-03	kg
KCl	Output	3.24E-05	kg
Magnesium	Output	1.24E-05	kg
Calcium	Output	1.72E-07	kg
Phosphorus	Output	1.67E-08	kg
Sulfur	Output	2.32E-09	kg
Iron	Output	1.38E-09	kg
Pre-dryer + condenser			
Electricity	Input	8.74	kJ
Heat	Input	82.70	kg
Waste water	Output	2.32E-02	kg
Steam Explosion + condenser			
Electricity	Input	6.12	kJ
Steam at 220 °C input (dry saturated)	Input	46.4	kJ
Heat	Input	70.2	kJ
Off-gas	Output	6.15E-03	kg
Energy from biogas	Output	33.8	kJ
Waste water	Output	1.89E-02	kg
Post dryer + condenser			
Electricity	Input	6.99	kJ
Heat	Input	97.85	kg

Waste water	Output	4.80E-02	kg
Pellet press + cooler			
Electricity	Input	23.30	kJ
Cooling water	Input/Output	6.47E-04	kg
Water vapor	Output	4.21E-03	kg
Product			
CAPCOM SCT pellet	Output	1	MJ

Empty Fruit Bunch

	Input/Output	*Amount*	*Unit /MJ pellet*
Empty Fruit Bunch (EFB)	Input	1.27	MJ
Size reduction step			
Electricity	Input	26.8	kJ
CC SMB extraction			
Electricity	Input	8.44	kJ
Water	Input	0.21	kg
Waste water	Output	0.17	kg
Water	Output	0.16	kg
Organic material	Output	6.25E-03	kg
KCl	Output	2.34E-03	kg
Magnesium	Output	1.82E-04	kg
Calcium	Output	4.96E-05	kg
Phosphorus	Output	6.62E-05	kg
Sulfur	Output	3.31E-05	kg
Screw press			
Waste water	Output	6.67E-02	kg
Water	Output	6.54E-02	kg
Organic material	Output	1.12E-03	kg
KCl	Output	5.95E-05	kg
Pre-dryer + condenser			
Electricity	Input	7.48	kJ
Heat	Input	40.2	kg
Waste water	Output	9.23E-03	kg
Steam Explosion + condenser			
Electricity	Input	5.87	kJ
Steam at 220 °C input (dry saturated)	Input	44.2	kJ
Heat	Input	67.0	kJ
Off-gas	Output	5.81E-03	kg
Energy from biogas	Output	31.9	kJ
Waste water	Output	1.81E-02	kg
Post dryer + condenser			
Electricity	Input	6.73	kJ
Heat	Input	92.18	kg
Waste water	Output	4.59E-02	kg
Pellet press + cooler			
Electricity	Input	22.24	kJ
Cooling water	Input/Output	5.95E-04	kg
Water vapor	Output	4.02E-03	kg
Product			
CAPCOM EFB pellet	Output	1	MJ

Sugarcane Bagasse

	Input/Output	*Amount*	*Unit /MJ pellet*
Bagasse	Input	1.11	MJ
Steam Explosion + condenser			
Electricity	Input	5.79	kJ
Steam at 220 °C input (dry saturated)	Input	43.9	kJ
Heat	Input	66.2	kJ
Off-gas	Output	5.79E-03	kg
Energy from biogas	Output	31.8	kJ
Waste water	Output	1.79E-02	kg
Post dryer + condenser			
Electricity	Input	6.71	kJ
Heat	Input	86.8	kg
Waste water	Output	4.67E-02	kg
Pellet press + cooler			
Electricity	Input	22.0	kJ
Cooling water	Input/Output	6.43E-04	kg
Water vapor	Output	3.99E-03	kg
Product			
CAPCOM bagasse pellet	Output	1	MJ

To explore
the potential
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Report 2180