sustainability

MDPI

Article

Energy and Environmental Aspects of Using Eucalyptus from Brazil for Energy and Transportation Services in Europe

Otavio Cavalett *, Sigurd Norem Slettmo and Francesco Cherubini

Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), NO7491 Trondheim, Norway; slettmo@stud.ntnu.no (S.N.S.); francesco.cherubini@ntnu.no (F.C.)

* Correspondence: otavio.cavalett@ntnu.no; Tel.: +47-4135-7720

Received: 10 October 2018; Accepted: 1 November 2018; Published: 6 November 2018

Abstract: The international market of woody biomass for bioenergy is expected to have a major role in future global scenarios aligning with a 2 or 1.5 °C target. However, the quantification of the environmental impacts of energy and transportation services from novel technologies and biomass production systems are yet to be extensively studied on a case-specific basis. We use a life cycle assessment approach to quantify environmental impacts of four bioenergy systems based on eucalyptus plantations established in abandoned pastureland in Brazil. The alternative bioenergy systems deliver energy and transportation services in Europe (cradle-to-gate analysis), including modern technologies for production of heat, electricity (with and without carbon capture and storage), and advanced liquid biofuels. We find that all bioenergy systems can achieve sizeable climate benefits, but in some cases at increased pressure in other impact categories. The most impacting activities are biomass transport stages, followed by eucalyptus stand establishment, and pellet production. An estimate of the potential large-scale bioenergy deployment of eucalyptus established in marginal areas in Brazil shows that up to 7 EJ of heat, 2.5 EJ of electricity, or 5 EJ of transportation biofuels per year can be delivered. This corresponds to a climate mitigation potential between 0.9% and 2.4% (0.29 and 0.83 GtCO_2 per year) of the global anthropogenic emissions in 2015, and between 5.7% and 16% of European emissions, depending on the specific bioenergy system considered. A sensitivity analysis indicated that the best environmental performance is achieved with on-site biomass storage, transportation of wood chips with trucks, pellets as energy carrier, and larger ship sizes. Our quantitative environmental analysis contributes to increased understanding of the potential benefits and tradeoffs of large-scale supply of biomass resources, and additional research can further improve resolution and integrate environmental impact indicators within a broader sustainability perspective, as indicated by the recently established sustainable development goals.

Keywords: biomass; life cycle assessment; pellets; short-rotation coppice; eucalyptus; climate change

1. Introduction

Bioenergy is expected to have an important role in global scenarios for achieving global low temperature stabilization targets. Using renewable energy sources to displace fossil fuels, enhancing terrestrial carbon sinks, and capturing and storing carbon are among the key mitigation options to achieve climate targets [1]. For example, the different Shared Socio-economic Pathways (SSPs) indicate that the demand for dedicated crops for bioenergy can range from less than 5000, up to about 20,000 million tonnes per year by 2100, corresponding to about 200–1500 million ha of land for dedicated energy crops [2,3]. In these scenarios, bioenergy deployment is often considered, in combination with technologies for capture and storage of carbon emissions (BECCS) [3]. BECCS allows achieving negative CO_2 emissions, after energy and transportation services are used to replace fossil fuels. However, many studies alert to the fact that feasibility of large-scale deployment of BECCS has not yet been demonstrated, nor have its potential and risks been fully examined [1,4–6].

The international market of forest biomass in the form of wood pellets have increased dramatically in the recent years, with Europe being the main importer and North America the main exporter [7–11], mostly due the Renewable Energy Directive (RED) [12]. In this policy, the European countries aim to increase the share of renewable energy in their gross final energy consumption to 20% by 2020. Much has been written about the environmental issues of this increasing use of woody biomass for bioenergy, e.g., [1,7,13–15], in terms of net climate change mitigation benefits, competition for land resources, and potential adverse side-effects on biodiversity and other ecosystem services. A large body of work has also quantified the life cycle greenhouse gas (GHG) emissions of wood pellets from short-rotation coppice (SRC) systems [16–25], roundwood [1,26–29], logging residues [8,25,30,31], and wood industry residues [32,33], as well as the energy and transportation services from the international market of wood pellets, e.g., [28,30,34–38]. Results, including the international trade of bioenergy products, usually suggest that the highest avoided emissions occur when wood pellets are used to replace energy systems from high-emission fossil fuel, such as coal e.g., [6–8]. For example, climate impacts savings are reported ranging between 50% and 85% for electricity derived from imported wood pellets from the United States, in comparison to electricity derived from fossil fuels in Europe [30,37]. Climate impacts related to wood pellet production and transatlantic shipment (e.g., from North America to Europe) are found to contribute as of approximately 50% and 30% of total climate impacts, respectively [37]. Other environmental impacts are reported, varying mostly due to technical aspects of the chosen bioenergy system (e.g., biomass production system, transportation, plant efficiency and technology), modelling assumptions, and methodological issues (e.g., methods to deal with the coproducts) [17–19,28].

High-density energy wood plantations managed on short-rotation coppice (SRC) are seen as a promising source of biomass for different final uses, since they could help to mitigate some of the environmental issues arising from using forest wood resources for bioenergy [17,18,39,40]. It is mostly because SRC production systems present relatively higher yields than conventional forestry systems [39], and the possibility to be gown on marginal land to reverse grassland degradation, thereby being beneficial under both a climate change mitigation and land restoration perspective [16,41].

To the best of our knowledge, no previous studies examined the environmental implications of alternative energy and transportation services in Europe form novel technologies and pioneering eucalyptus short-rotation coppice (SRC) systems in Brazil. This research gap is particularly important because many global temperature stabilization scenarios aligning with a 2 or 1.5 °C target predict a large increase in the biomass supply to the international markets, especially from land-rich regions, such as Latin America and Africa, to high energy-demanding regions, such as Europe and East Asia [2,3,42,43]. However, most of the existing literature focuses on the climate impacts of SRC systems in North America, e.g., [17,44], or Europe, e.g., [16,18,19,41], while a few focus on other regions, e.g., [27,40]. The environmental conditions and locations in which biomass resources grow considerably affect yields, management systems, and the product characteristics [40]. Wood pellets from eucalyptus SRC produced in Brazil are a promising option because eucalyptus is the most important forest species for wood supply in the country [39], and plantation trials have demonstrated that it is possible to double productivity when eucalyptus is grown under SRC management [45].

In this study, we apply the life cycle assessment (LCA) methodology to quantify relevant environmental impacts of different bioenergy systems delivering energy and transportation services in Europe from imported wood pellets from pioneering eucalyptus SRC systems produced in Brazil, including production of heat, electricity, advanced liquid biofuels, and BECCS. Using this approach, we aim to determine the best bioenergy systems to convert biomass resources in energy and transportation services in Europe, identify the supply chain stages with higher environmental impacts, and compare the environmental benefits and adverse side effects of bioenergy displacing fossil fuel products.

Finally, we carry out a comprehensive sensitivity analysis to address the influence of changes in key technical aspects, modelling assumptions, and methodological issues in the environmental impacts of bioenergy systems.

2. Materials and Methods

2.1. Life Cycle Assessment

The life cycle assessment (LCA) is a broadly recognized methodology to quantify relevant environmental impacts due to resource use and emissions to air, water, and soil, along the entire life cycle of products and services [46]. The general objective of LCA is to provide a comprehensive view of environmental impacts due to activities involved in the extraction, refining, transport, and use of the materials and fuels, considering direct and indirect inputs in the entire value chain. This study considers an attributional cradle-to-gate life cycle assessment of bioenergy systems delivering different energy and transportation services from eucalyptus SRC resources. Results are primarily compared using 1 tonne of biomass (dry basis) as reference flow. Environmental impacts are also presented as 1 GJ of energy and transportation services at factory gate to be benchmarked against each other and to the reference products derived from fossil fuels.

For the product systems with more than one output, exergy content of outputs is employed as allocation criterion based on similar studies considering combined heat and power (CHP) plants e.g., [47]. Specific exergy of electricity is assumed to be 1, while the exergy of heat is set to 0.309 J J^{-1} (considering water at 90 °C, based on simulations from [48], see allocation factors in Table S1). The modelled product systems are linked with the background processes from the ecoinvent database [49] using the software SimaPro v. 8.1.1 (see Tables S4–S6 for the individual life cycle inventory flows) [50]. Selected environmental impact categories from the CML-IA methodology, developed by the Center of Environmental Science (CML) of Leiden University in The Netherlands, are acidification potential (AP), eutrophication potential (EP), global warming potential (GWP, assessed with GWP100 only) with a 100 years' time horizon, and photochemical oxidant formation potential (POFP) [51]. These four categories were selected due their relevance to the bioenergy systems [16,17,32].

2.2. Description of the Bioenergy Systems

Four bioenergy systems are considered in this study, representing different conversion options in Europe for pellets from eucalyptus SRC systems produced in Brazil. The product systems include the entire value chain of bioenergy systems, from seedling production to eucalyptus wood harvesting, chipping, pellet production, transportation systems (including transatlantic shipping), and conversion to energy and transportation services in Europe, as depicted in Figure 1. Selected inputs form background systems are exemplified in this diagram.

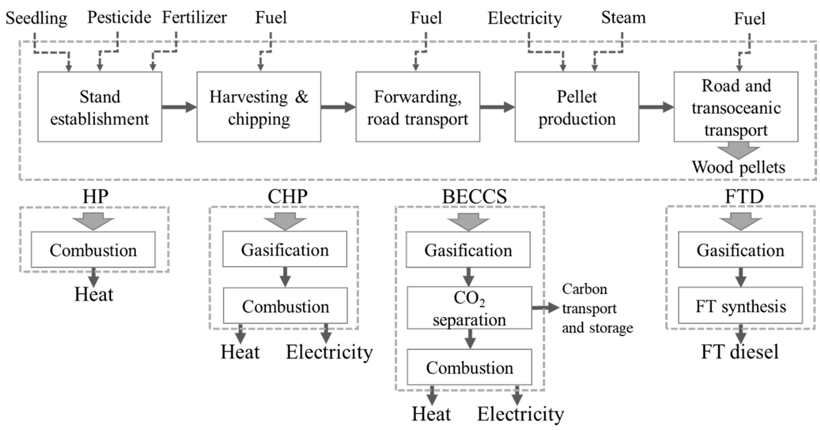

Figure 1. Product system modelled for the bioenergy systems delivering energy and transportation services in Europe.

2.3. Wood Pellet Production

2.3.1. Eucalyptus Short-Rotation Coppice System

The biomass production system is modelled considering a eucalyptus (*Eucalyptus. urograndis*) short-rotation coppice (SRC) produced in the state of São Paulo, Brazil. The eucalyptus SRC system was modelled based on data from ref. [39], selecting data maximizing yield under the constraint of lower fertilization levels. The emission inventories of eucalyptus SRC system considers seedling production, soil preparation, fertilization, planting, and harvesting. The production system is characterized by dense stands of plants (more than 7000 trees ha^{-1}) and biomass harvesting every 2 years. During the harvesting operation, all aboveground biomass (stem, branches, and leaves) is chipped, and not debarked stems, as in conventional eucalyptus plantations [39]. Biomass yield in eucalyptus SRC system is assumed as 19 tonne$_{(db)}$ ha^{-1} year^{-1} with a carbon content of 44.8% (see Table S2 for details about biomass characteristics) [39]. Yields have been known to decline in SRC stands after five harvesting cycles (i.e., 10 years), and re-establishment of stands may be necessary after this period [52,53]. The biomass harvesting operation considers modern cut-and-chip harvester [54], and wood chip loading is also included in the life cycle inventory [32]. On-site biomass drying from 63% to 35% moisture$_{(wet\ basis)}$ is included to reduce transportation impacts [55]. Biomass losses of 2% in mass$_{(db)}$ are considered at this stage [30,56,57].

2.3.2. Wood Pellet Production

In general, pellet production promotes the conversion of woody resources into a uniform product with superior combustion properties and improved performance in terms of handling, transportation, storage, and combustion performance [19]. Wood pellets are produced from the eucalyptus wood chips in a pellet plant. The pellet production process comprises mechanical drying, grinding, and densification stages [28,32]. This process presents relatively high energy demand, both in the form of heat and electricity. Wood pellets are considered with 5% moisture$_{(wb)}$ [58] and additional biomass losses of 2% in mass$_{(db)}$ are considered at this stage. Low moisture content of pellet production is recognized as an important parameter to rationalize long-distance transportation systems from Brazil to Europe.

2.3.3. Transportation Systems

Four transportation stages are included in the product system. The first one is the forwarding of harvested eucalyptus chips to the pellet plant (50 km). Next, the pellets are transported from the pellet plant to the port of departure in Brazil (320 km), followed by the transatlantic shipping to Europe (11,000 km) [59]. The final step is transportation, from the port of arrival in Europe to the industrial plant where the feedstock is converted into the different energy and transportation services (10 km). The mode of all road transportation systems is considered to be trucks with high loading capacity (>32 tonnes). Detailed information on the transportation systems is provided in Table S3.

2.4. Bioenergy Conversion Plants

We considered four bioenergy systems for the conversion of the wood pellets in Europe. They are a heat plant (i); a combined heat and power plant without (ii) and with (iii) carbon capture and storage facility; and a plant converting wood pellets in synthetic diesel for transportation using gasification and Fischer–Tropsch synthesis (iv). Table 1 provides a summary of the process efficiencies, including energy services output per tonne of biomass processed and per hectare-year. The conversion efficiencies were adjusted from literature data, aiming to better represent the lower moisture content of wood pellets instead to wood chips. Complete life cycle inventory information is provided in Tables S4–S6.

Table 1. Energy conversion efficiencies and outputs for the different industrial conversion technologies.

Bioenergy System	Energy and Transportation Service	Conversion Efficiency (%) [a]	Adjusted Conversion Efficiency (%) [b]	Energy Output (GJ tonne^{-1})	Energy Output (GJ ha^{-1} year^{-1})
Heat plant (HP)	heat	80.0 [c]	80.9	14.7	279.2
Combined heat and power plant (CHP)	electricity	27.8 [d]	28.7	5.20	99.0
	heat	50.8 [d]	52.4	9.50	180.9
Combined heat and power with carbon capture and storage (BECCS)	electricity	22.7 [d]	23.4	4.24	80.9
	heat	48.2 [d]	49.8	9.01	171.7
Fischer–Tropsch diesel (FTD)	FT diesel	46.7 [e]	54.3	9.83	187.2

[a] Conversion efficiency as reported in the original reference. [b] Conversion efficiency adjusted to wood pellets instead of wood chips, proportionally to the lower water content of pellets. [c] [49]. [d] [48,60]. [e] [61,62].

2.4.1. Heat Plant (HP)

The heat plant is modelled from a modern small-to-medium scale (300 kW) wood chip furnace in the ecoinvent database [49]. This inventory is adapted to consider wood pellets instead of wood chips. The plant is equipped with modern pollution control technologies, including filters and an electrostatic precipitator for particulate matter. The emission inventory includes infrastructure, industrial inputs, emission to air, and the disposal of ashes. In this bioenergy system, heat (at the factory gate) is the only energy service output. The heat plant has a considerably smaller scale than the other conversion options. This is to reflect the fact that district heating is normally generated with decentralized facilities, linking production and consumption within short distances, to avoid major heat losses. This is opposed to the processes based on gasification of biomass, where larger scales are preferable to rationalize high capital cost of the gasification plant. Although scale is a major issue in economic analyses, some environmental studies have addressed the importance of scale in the environmental assessment of energy systems, indicating little effects for the environmental assessment of stationary bioenergy plants [47,63,64]. Therefore, no major deviances in the results are expected here, due to differences of scale in the bioenergy plants.

2.4.2. Combined Heat and Power Plant (CHP)

The combined heat and power plant considers a modern medium scale (10 MW) biomass gasification plant coupled to a gas engine. Gasification is a high-temperature partial oxidation of solid material containing carbon with air, steam, or oxygen, into a gas mixture called synthesis gas or syngas, which is primarily composed of CO and H_2, and contains various amounts of CO_2, H_2O, and CH_4. Several gasifier configurations have been proposed, and advantages and disadvantages of each configuration have been extensively documented, e.g., [65]. In our study, the biomass is converted into syngas in a fast internally circulating fluidized bed (FICFB) unit. Syngas is then fed into a gas engine for electricity generation. In addition to electricity, heat is also coproduced by recovering heat from both the gasifier and the gas engine. The life cycle inventory modelling is based on data from [48,60].

2.4.3. Combined Heat and Power with Carbon Capture and Storage (BECCS)

In this bioenergy system, a carbon capture and storage facility are implemented into a CHP power plant, equivalent to the one in the CHP system. This set up allows achieving negative CO_2 emissions. Carbon capture considers pre-combustion and adsorption of CO_2, with pressure-vacuum swing [48,60]. After gasification, 90% of the CO_2 in the flue gas is recovered, considering an overall capture rate of 49%. The captured CO_2 is compressed, and considered to be transported through about 200 km for storage in a saline aquifer using a pipeline [66]. Following the same approach as Singh et al., we assume that one-third of the diameter of pipeline is used to transport the compressed liquid CO_2 [67]. Pipeline and injection well data was retrieved from the ecoinvent database [68]. During the handling and storage period, some CO_2 is lost to the atmosphere as fugitive emissions, and these are to be discounted to the total amount of captured carbon. The rate of fugitive CO_2 was set as 290 mg kg^{-1}

CO_2 [69]. The CO_2 is stored in geological formations during enough time to justify being accounted for as negative CO_2 emissions, since the carbon in wood pellets is of biological origin (biogenic). In the results, these negative CO_2 emissions are indicated as part of carbon capture and storage stage.

2.4.4. Fischer–Tropsch Diesel (FTD)

This bioenergy system considers the biomass gasification process similar to CHP, but here syngas is catalytically converted into synthetic liquid fuels with varied chain length using Fischer–Tropsch synthesis. The catalyst, process conditions, and design of the catalysis reactor ultimately determines the product mix, including methane, liquefied petroleum gas, gasoline, jet fuel, diesel, and waxes. The process data was compiled from refs. [61,62]. The additional life cycle phases of fuel distribution and vehicle operation were included in the emission inventories to compare Fischer–Tropsch diesel and conventional fossil diesel.

2.5. Large-Scale Bioenergy Deployment

Pastureland is the largest land use in Brazil, comprising about 230 Mha [70]. More than half of the pasture area in Brazil is associated to some degree of degradation, and challenges remain to reverse grassland degradation [71]. We look at potential impacts of large-scale bioenergy deployment considering the introduction of 25 million hectares of eucalyptus SRC systems in marginal areas in Brazil. These marginal areas are considered to be previously occupied with pastureland under some degree of degradation [70,72] and, due to lower yields, continued intensification in livestock production systems and societal dietary changes [73,74] are considered to be available for bioenergy production. In addition, SRCs production systems grown on marginal lands are identified as beneficial from a land use perspective, mainly when used to reverse grassland degradation, as they can increase soil carbon stocks and many key ecosystem services (including biodiversity) [15,16,41]. This reduces possible concerns regarding additional pressure of bioenergy systems on productive agricultural land, and minimizes competition with other land uses [75]. Results are then compared to the current European demand of heat and electricity derived from the International Energy Agency (IEA) considering the 28 EU countries [76] and transportation liquid fuels from [77]. Environmental impacts are also related to global anthropogenic emissions of fossil fuels in 2015 [78], and European environmental impacts from the normalization scores of the CML-IA methodology [51].

2.6. Climate Impacts from Changes in Land Use

Land use changes are intrinsically uncertain to model, and difficult to reverse since, for example, pasture abandonment does not lead to the spontaneous restoration of original old-growth ecosystems [79]. Despite the fact that conversion of pasture to annual crops is the most frequent conversion in Brazil [80], its conversion to forest or perennial bioenergy crops is likely to promote many environmental benefits, including the increase in soil carbon stocks [81,82]. However, we take a conservative assumption that production of eucalyptus SRC systems do not increase soil carbon stocks when produced in areas previously occupied with pasture, with some degree of degradation in Brazil. This assumption in supported by a meta-analysis of 101 sites planted with eucalyptus SRC in São Paulo state, that showed little to no change (0.06 tC ha^{-1} $year^{-1}$) after 20 years of harvest rotations, while overall in 306 sites in Brazil showed a minor emission of 0.11 tC ha^{-1} $year^{-1}$ [83].

3. Results

The breakdown of environmental impacts over the life cycle stages is presented in Figure 2. In these results, unallocated environmental impacts are presented as having 1 $tonne_{(db)}$ of eucalyptus SRC pellets processed in the four bioenergy systems as the reference flow. The shipping of pellets from Brazil to Europe has remarkably high impacts in most of the environmental impact categories. Eucalyptus SRC establishment has high impacts on eutrophication (EP) and acidification (AP), notably due to use of nitrogen fertilizers. The pellet production stage presents a significant contribution to climate change (GWP100) and photochemical oxidant formation (POFP), mostly because of its high power and thermal energy demand. Harvesting and chipping of eucalyptus SRCs shows relatively moderate contribution to the selected environmental impacts. The BECCS bioenergy system undoubtedly promotes a significant reduction in the climate impacts, while additional inputs needed to capture, compress, transport, and store the carbon account for only 3% of its total climate impacts.

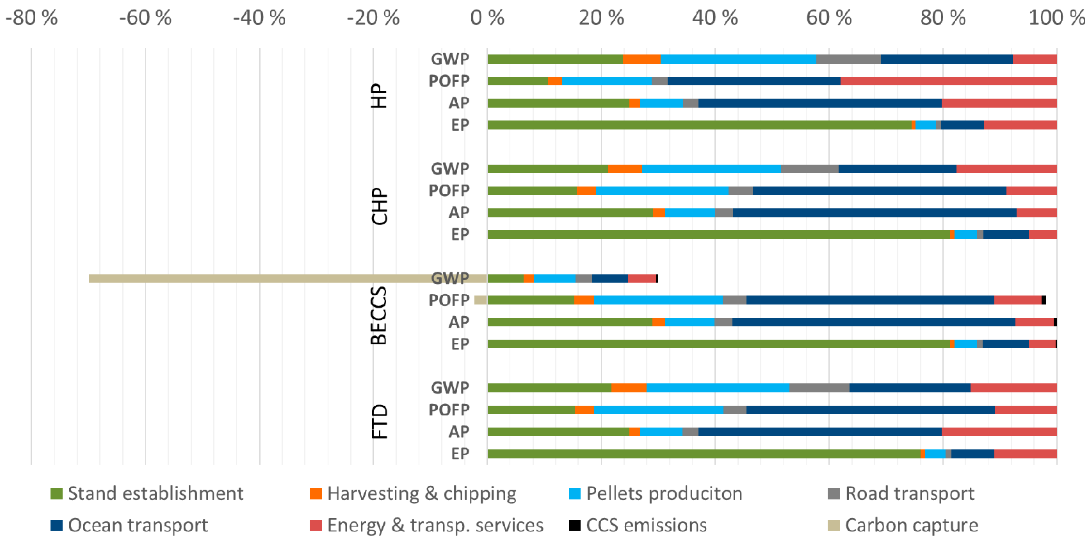

Figure 2. Breakdown of environmental impacts from the four selected bioenergy system options for production of energy and transportation services.

The environmental impacts of different energy and transportation services provided by the four bioenergy systems are presented in Table 2. In this table, environmental impacts are allocated to the different outputs based on the exergy content of outputs, as described in the methods section. Fossil fuels impacts are also presented in the table as reference systems. All the energy and transportation services from eucalyptus SRC pellets presented lower climate impacts in comparison with fossil counterparts. The second lower climate impacts for heat and electricity production is obtained with the CHP system, logically after BECCS, which yields negative CO_2 emissions.

Considering the other environmental impact categories, HP and FTD options presented higher impacts than to fossil references. These aspects are better visualized in Table 3, where environmental impacts per $tonne_{(db)}$ of eucalyptus SRC processed are shown before and after substitution of their fossil reference systems. Most of the bioenergy systems presented slightly higher impacts on EP and AP in comparison to fossil reference systems; however, these categories have a local scope and, therefore, especially important for consideration in site-specific development projects. The CHP and BECCS options reduce environmental impacts in POFP and AP categories when substituting its fossil references. This is mostly due to the electricity from wood pellets substituting electricity from natural gas. In all the bioenergy systems, EP impacts are higher for the bioenergy systems in comparison to the fossil references, due to the use of fertilizers in eucalyptus SRC production systems.

Table 2. Environmental impacts for the energy and transportation services provided by the four bioenergy systems and fossil references systems.

Bioenergy System	Energy and Transportation Service	Unit	Climate Change (kg CO_2eq. unit^{-1})	Photochemical Oxidant Formation (kg C_2H_4eq. unit^{-1})	Acidification (kg SO_2eq. unit^{-1})	Eutrophication (kg PO_4^{3-}eq. unit^{-1})
Heat plant (HP)	Heat	GJ^{-1}	19.9	0.013	0.252	0.159
Combined heat and power plant (CHP)	Heat	GJ^{-1}	13.8	0.005	0.128	0.085
	Electricity	GJ^{-1}	39.5	0.017	0.396	0.269
Combined heat and power with carbon capture and storage (BECCS)	Heat	GJ^{-1}	−19	0.006	0.147	0.098
	Electricity	GJ^{-1}	−66.7	0.019	0.410	0.338
	Carbon capture	tC^{-1}	−2.11	0.001	0.015	0.010
Fischer–Tropsch diesel (FTD)	Fuel production	GJ^{-1}	32.3	0.014	0.376	0.233
Fossil reference	Heat	GJ^{-1}	73.4	0.007	0.097	0.023
	Electricity	GJ^{-1}	153	0.029	0.597	0.025
	Fossil diesel	GJ^{-1}	84.8	0.010	0.271	0.054

Table 3. Environmental impacts per tonne$_{(db)}$ of biomass processed in the bioenergy systems before (B) and after substitution (A) of their fossil reference systems.

Impact Category	Unit	Heat Plant (HP)		Combined Heat and Power Plant (CHP)		Combined Heat and Power with Carbon Capture and Storage (BECCS)		Fischer-Tropsch Diesel (FTD)	
		B	**A**	**B**	**A**	**B**	**A**	**B**	**A**
Climate change	kg CO_2eq. tonne^{-1}	292	−784	327	−1165	−437	−1748	318	−620
Photochemical oxidant formation	kg C_2H_4eq. tonne^{-1}	0.20	0.09	0.13	−0.09	0.13	−0.06	0.14	0.04
Acidification	kg SO_2eq. tonne^{-1}	3.70	2.27	3.18	−0.85	3.18	−0.23	3.70	2.05
Eutrophication	kg PO_4^{3-}eq. tonne^{-1}	2.34	2.00	2.14	1.79	2.14	1.83	2.29	1.97

4. Discussion

Climate impacts in Table 2 are generally in accordance with reported ranges for heat, electricity, and transportation services from wood [84] and short-rotation woody crops [6]. Also, climate impacts of heat production in HP and CHP bioenergy systems are similar to heat production from SRC systems using willow in Canada [17], poplar in Spain [19], and eucalyptus in France [18]. Electricity impacts are also similar to electricity from forest residues produced in the United States and transported to United Kingdom [30]. However, it should be noted that the climate impacts of CHP systems, based on wood feedstock, present high variability in the literature [84]. Similarly, emission savings ranging from 61 to 115% for FT diesel, compared to fossil diesel, are reported for biomass-to-liquid fuels [85], in accordance with our results, indicating a 66% reduction in climate impacts in comparison to using fossil diesel.

These results from the other environmental impact categories confirm previous analyses, indicating higher EP impacts for bioenergy systems from wood pellets in comparison to fossil fuels [17–19]. The bioenergy system considering Fischer-Tropsch diesel production is the option with the lowest climate change mitigation potential after substitution, meaning the lower climate benefit per tonne(db) of processed biomass. It occurs mainly because heat and electricity are considered to substitute relatively "dirty" natural gas power plants in the present study [49]. Some studies call the attention that there are more alternatives for decarbonize electricity and heat (e.g., solar, wind, hydro, etc.) than liquid fuels for transportation demand [86]. Therefore, the potential deployment of liquid transportation fuels from Fischer-Tropsch option remains, especially in regions of increasing demand for liquid fuels and lower capacity of investments for major changes in transportation infrastructure (e.g., massive introduction of electric mobility systems), such as Southeast Asia and Latin America.

4.1. Sensitivity Analysis

A sensitivity analysis was performed to address how changes in key technical aspects, modelling assumptions, and methodological issues, would affect the environmental impacts of the different bioenergy systems. See Table S7 for details on the life cycle modelling changes implemented in the sensitivity analysis. The sensitivity results in Table 4 are shown as a percent change in the unallocated environmental impacts and total energy output per $tonne_{(db)}$ of processed biomass, in relation to the indicated reference system (selected from one of the evaluated bioenergy systems in this study).

Our analysis indicated that alternative modelling choices in the bioenergy systems might significantly alter the results. For example, considering higher moisture content in wood pellets (from 5% to 10%) increased impacts to all categories, except climate change, due to lower energy output (−6.2%). Using wood chips instead of pellets as energy carrier significantly promote higher impacts, due to lower thermal efficiency of wood chips in comparison to wood pellets. In addition, higher degradation of biomass is expected for wood chips, being translated into the lower energy yields (−10.3%). Torrefaction of pellets is seen an interesting improvement to reduce climate impacts in this value chain [28]. In this alternative, biomass goes through a torrefaction process before the densification stage. The use of torrefied biomass, both as lose material or pellets, can promote lower environmental impacts in comparison to wood pellets, mainly due to more efficient intercontinental transportation system. Torrefaction is identified as a promising alternative from the environmental impact perspective, but at the cost of significant reduction in the energy output. In addition, it is important to highlight that lost torrefied biomass is an uncommon energy carrier, therefore, unlikely to be traded in the international market without any densification step [87].

Different background energy mixes were investigated for pellet production and FTD processes, since they present comparatively high energy demands. Using additional wood chips as energy source for the pellet production process promoted a reduction on environmental impacts in relation to the reference bioenergy system. However, this would introduce an additional demand on external biomass (and, consequently, more resources, land, etc.). If these impacts are included in the product system cannibalizing some of the wood chip feedstock for providing the energy demand for the pelletizing process, the reduction in energy output is expressive (−8.2%). The emissions in Brazilian electricity mix were found to be particularly high in comparison to similar processes in other countries, mainly due to emissions of CO_2 and CH_4 from flooded areas for hydropower production (the highest share in the Brazilian electricity mix, of about 70%). These emissions are highly uncertain, and obviously should be properly depreciated during the life span of the hydropower plant [88]. Excluding CO_2 and CH_4 emissions in the hydropower process led to a decrease in the climate impacts of about 11%, and a minor decrease in POFP in comparison to the reference system. Considering, the FTD process located in Brazil causes a decrease in all categories, except for climate change. This is mainly due to the differences in the energy mixes between Brazil and the reference energy mix adopted for the reference country used in Europe (i.e., Norway).

The sensitivity to higher fertilizer inputs in eucalyptus SRC systems assumes figures that are about four times higher than the reference case, reflecting the faster growing rates reported in ref. [39]. Our results indicated that higher impacts due the higher fertilization rates are not compensated by the higher energy outputs. The use of a smaller ship size, for transoceanic transportation of pellets from Brazil to Europe, is translated to an increase in about 5% to 30% on the various environmental impact categories, highlighting the importance of transportation systems in the results. In particular, it draws attention to more efficient long-haul marine transportation systems. Higher impacts are also observed when using a tractor for forwarding wood instead of a large lorry, once more, highlighting the importance of efficient transportation systems in the bioenergy value chains. Transporting wet biomass to the pellet factory will increase road transportation emissions. However, these impacts are relatively small in comparison to the other supply chain alternatives' sensitivities presented here. Finally, the alternative of performing carbon capture and storage by using the post-combustion absorption [48] increases environmental impacts and decreases energy output, mainly because this technology requires additional energy inputs in comparison to the reference case for carbon capture and storage facility.

4.2. Large-Scale Bioenergy Deployment

The quantification of energy outputs and environmental impacts from an idealized large-scale bioenergy deployment, with the introduction of 25 million hectares of SRC eucalyptus in Brazil being used for bioenergy production in Europe, is presented in Tables 5 and 6. In this exercise, we assume that SRC eucalyptus plantations are established on marginal areas previously occupied with pastureland. This premise avoids concerns about the additional pressure of bioenergy systems on productive agricultural land, while minimizing competition with other land uses. This ideal analysis is performed to estimate a benchmark for the possible environmental profile of a large-scale bioenergy production as envisioned by many future energy scenarios.

The considered large-scale bioenergy deployment would be able to deliver significant shares of current energy and transportation demands in Europe (Table 5). Highest energy services are obtained with the HP and CHP. With the idealized large-scale bioenergy deployment, the heat demand in Europe can be outreached by approximately 2 to 3 times, while the demand of liquid fuel for transportation is attained by 34%, and electricity by 18% to 22%, depending on the bioenergy system. BECCS is a very promising bioenergy alternative regardless of presenting the smallest energy output. The magnitude of the environmental impacts due to large-scale bioenergy deployment in Table 6 results from the upscaling of figures shown in Table 2. The energy and transportation services produced in the different bioenergy systems achieve a reduction between 0.9% and 2.4% of global CO_2 emissions in 2015. When compared to emissions from Europe only, large-scale bioenergy deployment is able to provide climate change mitigation between 5.7% and 16%. For the other environmental impact categories and their effects on European total impacts, results largely vary for the different bioenergy systems. POFP is increased with HP (1.7%) and FTD (0.7%), but decreased with CHP (1.5%) and BECCS (1.0%). AP shows the same trend, although with larger relative increases (6.4% for HP and 5.8% for FTD). EP impacts uniformly increase between 4.6 and 5.1%. BECCS delivers the smallest fraction of energy service (Table 5), but it achieves the highest emission savings, while presenting moderate co-benefits in POFP and AP, and the smallest trade-offs in EP in comparison to the other bioenergy systems considered here.

Table 4. Sensitivity analysis on environmental impacts and energy outputs for selected life cycle modelling assumptions. GWP100 climate change with a 100 years' time horizon; POFP: photochemical oxidant formation; AP: acidification; EP: eutrophication.

Change in the Product System		Reference Bioenergy System	GWP100 (%)	POFP (%)	AP (%)	EP (%)	Energy (%)
Energy carrier	Higher moisture pellets	HP	−1.3	1.6	2.3	0.6	−6.2
	Wood chips	HP	3.6	156.2	46.9	35.5	−10.3
	Torrefied pellets	HP	−23.1	−19.6	−5.1	−19.0	−5.1
	Torrefied biomass (lose)	HP	−1.3	1.6	2.3	0.6	−6.2
Background energy	Additional chips as pellets production heat	HP	−1.5	1.6	-	0.5	0.0
	Own chips as pellets production heat	HP	−0.1	−0.3	−0.8	-	−8.2
	No direct emissions in Brazilian electricity mix	HP	−10.9	−1.3	-	-	-
	FTD production in Brazil	FTD	14.5	−3.4	−24.1	−2.6	0.0
Supply chain choices	High fertilizer input	HP	37.3	13.8	59.0	203.1	1.4
	Smaller ship size	HP	20.7	14.2	30.0	5.2	-
	Forwarding with tractor	HP	15.0	9.4	8.9	3.6	-
	No on-site drying	HP	1.5	0.4	0.4	0.1	-
End use	Absorption carbon capture and storage	BECCS	28.6	7.8	1.0	0.5	−11.9

Table 5. Large-scale energy outputs of bioenergy systems providing energy and transportation services in Europe [a] from eucalyptus SRC produced in Brazil. Energy outputs are also shown as relative to the European demand.

Bioenergy System	Bioenergy Output (EJ year^{-1})			Bioenergy Output Relative European Demand of Energy and Transportation Services (%)		
	Heat	Electricity	Fuel	Heat	Electricity	Fuel
Heat plant (HP)	6.98	-	-	300	-	-
Combined heat and power plant (CHP)	4.52	2.48	-	194	22	-
Combined heat and power with carbon capture and storage (BECCS)	4.29	2.02	-	184	18	-
Fischer–Tropsch diesel (FTD)	-	-	4.95	-	-	34

[a] European demand in 2014 is considered as of 2.3 EJ year^{-1} for heat [76], 11.5 EJ year^{-1} for electricity [76], and 14.8 EJ year^{-1} for liquid transportation fuels [77] (see Section 2.5).

Table 6. Large-scale environmental impacts of bioenergy systems providing energy and transportation services in Europe from eucalyptus SRC produced in Brazil. Bioenergy impacts are also shown as relative to the Global and European total impacts for each investigated environmental category.

Bioenergy System	Environmental Impacts of Bioenergy Systems after Substituting Fossil Reference Products				Bioenergy Impacts Relative to Global [a] and European [b] Impacts				
	Climate Change (kg CO_2eq. $year^{-1}$)	Photochemical Oxidant Formation (kg C_2H_4eq. $year^{-1}$)	Acidification (kg SO_2eq. $year^{-1}$)	Eutrophication (kg PO_4^{3-} eq. $year^{-1}$)	Global Climate Impacts (%)	European Climate Impacts (%)	European Photochemical Oxidant Formation Impacts (%)	European Acidification Impacts (%)	European Eutrophication Impacts (%)
Heat plant (HP)	-3.7×10^{11}	4.4×10^{7}	1.1×10^{9}	9.5×10^{8}	−1.1	−7.2	1.7	6.4	5.1
Combined heat and power plant (CHP)	-5.5×10^{11}	-4.1×10^{7}	-4.1×10^{8}	8.5×10^{8}	−1.6	−10.6	−1.5	−2.4	4.6
Combined heat and power with carbon capture and storage (BECCS)	-8.3×10^{11}	-2.7×10^{7}	-1.1×10^{8}	8.7×10^{8}	−2.4	−16.0	−1.0	−0.6	4.7
Fischer–Tropsch diesel (FTD)	-2.9×10^{11}	1.8×10^{7}	9.7×10^{8}	9.3×10^{8}	−0.9	−5.7	0.7	5.8	5.1

[a] [78]; [b] [51].

5. Conclusions and Future Work

All the energy and transportation services from eucalyptus SRC pellets presented lower climate impacts in comparison with fossil counterparts. However, most of them presented slightly higher impacts on EP and AP. Results indicate that the combined heat and power plant with carbon capture and storage is the best option to convert imported biomass from SRCs of eucalyptus in Brazil, in terms of maximizing climate change mitigation. However, this can raise the environmental impacts in acidification, photochemical oxidant formation, and eutrophication, in relation to the reference fossil system. The most impacting activities in the life cycle of a bioenergy chain are primarily attributable to the biomass transport stages (including transoceanic shipping), followed by eucalyptus SRC stand establishment and, finally, the pellet production process. Our sensitivity analysis indicated that bioenergy systems with best environmental performance include on-site biomass storage, transportation of wood chips with trucks, use of pellets as an energy carrier, and large ship sizes for transoceanic transportation. This study supports that the international market of densified biomass from eucalyptus SRC systems is an interesting alternative to decarbonize the transport and energy sectors in Europe. Bioenergy options addressed here are appreciated as a sizeable climate change mitigation measure, without major burden shifting in other relevant environmental impact categories, although there can be some adverse side-effects that should be managed and mitigated. Future refining of the life cycle inventory modelling of energy and transportation services from eucalyptus SRC, during its initial deployment, will be instrumental to identify, manage, and prevent potential conflicting implications of biofuel systems in several environmental areas of concern. Our analysis considered only climate impacts from the life cycle of well-mixed greenhouse gases emissions, such as CO_2, CH_4 N_2O, and some fluorinated species. Further refinement in this analysis can entail the contribution of short-lived climate forcers (such as NOx, SOx, organic carbon, and black carbon) [89–91], biophysical aspects such as changes in albedo and evapotranspiration following establishment of eucalyptus plantation [92,93], potential changes in biogenic carbon dynamics [94,95], as well as applying complementary climate metrics tacking into consideration heterogeneities in the climate system response [89,90,96]. In addition, the inclusion of other relevant environmental impact categories that are normally included in the bioenergy debate, such as water depletion and biodiversity, would provide a better understanding of the co-benefits and tradeoffs between the multiple environmental sustainability implications of bioenergy systems. The inclusion of these aspects in a consistent life cycle assessment framework will allow a better representation of the various environmental challenges our society is facing, as recognized by the Sustainable Development Goals (SDG) agenda.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/10/11/4068/s1, Table S1: Allocation factors based on exergy outputs, Table S2: Summary of characteristics for eucalyptus SRC biomass, Table S3: Distances and modals used in the transportation system modelling, Table S4: Input flows for the eucalyptus short-rotation coppice and pellet production, Table S5: Input flows for the bioenergy systems producing energy and transportation services, Table S6: Emissions to air, soil and water from bioenergy systems producing energy and transportation services, Table S7: Summary of the life cycle modelling changes implemented in the sensitivity analysis.

Author Contributions: Conceptualization, S.N.S. and F.C.; Methodology, O.C., S.N.S. and F.C.; Software, O.C. and S.N.S.; Formal Analysis, Investigation, Resources, and Data Curation, O.C., S.N.S. and F.C.; Writing—Original Draft Preparation, O.C. and S.N.S.; Writing—Review and Editing, O.C. and F.C.; Visualization, O.C.; Project Administration and Funding Acquisition, F.C.

Funding: This research was funded by The Research Council of Norway, grant number 257622.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Birdsey, R.; Duffy, P.; Smyth, C.; Kurz, W.A.; Dugan, A.J.; Houghton, R. Climate, economic, and environmental impacts of producing wood for bioenergy. *Environ. Res. Lett.* **2018**, *13*, 050201. [CrossRef]

2. Popp, A.; Calvin, K.; Fujimori, S.; Havlik, P.; Humpenöder, F.; Stehfest, E.; Bodirsky, B.L.; Dietrich, J.P.; Doelmann, J.C.; Gusti, M.; et al. Land-use futures in the shared socio-economic pathways. *Glob. Environ. Chang.* **2017**, *42*, 331–345. [CrossRef]
3. Bauer, N.; Calvin, K.; Emmerling, J.; Fricko, O.; Fujimori, S.; Hilaire, J.; Eom, J.; Krey, V.; Kriegler, E.; Mouratiadou, I. Shared socio-economic pathways of the energy sector–quantifying the narratives. *Glob. Environ. Chang.* **2017**, *42*, 316–330. [CrossRef]
4. Vaughan, N.E.; Gough, C.; Mander, S.; Littleton, E.W.; Welfle, A.; Gernaat, D.E.; van Vuuren, D.P. Evaluating the use of biomass energy with carbon capture and storage in low emission scenarios. *Environ. Res. Lett.* **2018**, *13*, 044014. [CrossRef]
5. Smith, P.; Davis, S.J.; Creutzig, F.; Fuss, S.; Minx, J.; Gabrielle, B.; Kato, E.; Jackson, R.B.; Cowie, A.; Kriegler, E. Biophysical and economic limits to negative CO_2 emissions. *Nat. Clim. Chang.* **2016**, *6*, 42. [CrossRef]
6. Creutzig, F.; Ravindranath, N.H.; Berndes, G.; Bolwig, S.; Bright, R.; Cherubini, F.; Chum, H.; Corbera, E.; Delucchi, M.; Faaij, A. Bioenergy and climate change mitigation: An assessment. *Gcb Bioenergy* **2015**, *7*, 916–944. [CrossRef]
7. Dale, V.H.; Kline, K.L.; Parish, E.S.; Cowie, A.L.; Emory, R.; Malmsheimer, R.W.; Slade, R.; Smith, C.T., Jr.; Wigley, T.B.; Bentsen, N.S. Status and prospects for renewable energy using wood pellets from the southeastern United States. *Gcb Bioenergy* **2017**, *9*, 1296–1305. [CrossRef]
8. Porsö, C.; Hammar, T.; Nilsson, D.; Hansson, P.-A. Time-dependent climate impact and energy efficiency of internationally traded non-torrefied and torrefied wood pellets from logging residues. *BioEnergy Res.* **2018**, *11*, 139–151. [CrossRef]
9. Junginger, M.; Bolkesjø, T.; Bradley, D.; Dolzan, P.; Faaij, A.; Heinimö, J.; Hektor, B.; Leistad, Ø.; Ling, E.; Perry, M. Developments in international bioenergy trade. *Biomass Bioenergy* **2008**, *32*, 717–729. [CrossRef]
10. Junginger, M.; Van Dam, J.; Zarrilli, S.; Mohamed, F.A.; Marchal, D.; Faaij, A. Opportunities and barriers for international bioenergy trade. *Energy Policy* **2011**, *39*, 2028–2042. [CrossRef]
11. Lamers, P.; Junginger, M.; Hamelinck, C.; Faaij, A. Developments in international solid biofuel trade—An analysis of volumes, policies, and market factors. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3176–3199. [CrossRef]
12. EU. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. *Off. J. Eur. Union* **2009**, *5*, 2009.
13. Schlesinger, W.H. Are wood pellets a green fuel? *Science* **2018**, *359*, 1328–1329. [CrossRef] [PubMed]
14. Cornwall, W. Is wood a green source of energy? Scientists are divided. *Science* **2017**, *355*, 18–21. [CrossRef] [PubMed]
15. Robertson, G.P.; Hamilton, S.K.; Barham, B.L.; Dale, B.E.; Izaurralde, R.C.; Jackson, R.D.; Landis, D.A.; Swinton, S.M.; Thelen, K.D.; Tiedje, J.M. Cellulosic biofuel contributions to a sustainable energy future: Choices and outcomes. *Science* **2017**, *356*, eaal2324. [CrossRef] [PubMed]
16. Schweier, J.; Schnitzler, J.-P.; Becker, G. Selected environmental impacts of the technical production of wood chips from poplar short rotation coppice on marginal land. *Biomass Bioenergy* **2016**, *85*, 235–242. [CrossRef]
17. Dias, G.M.; Ayer, N.W.; Kariyapperuma, K.; Thevathasan, N.; Gordon, A.; Sidders, D.; Johannesson, G.H. Life cycle assessment of thermal energy production from short-rotation willow biomass in Southern Ontario, Canada. *Appl. Energy* **2017**, *204*, 343–352. [CrossRef]
18. Gabrielle, B.; Maupu, P.; Vial, E. Life cycle assessment of eucalyptus short rotation coppices for bioenergy production in southern France. *Gcb Bioenergy* **2013**, *5*, 30–42. [CrossRef]
19. Ruiz, D.; San Miguel, G.; Corona, B.; Lopez, F. LCA of a multifunctional bioenergy chain based on pellet production. *Fuel* **2018**, *215*, 601–611. [CrossRef]
20. Caputo, J.; Balogh, S.B.; Volk, T.A.; Johnson, L.; Puettmann, M.; Lippke, B.; Oneil, E. Incorporating uncertainty into a life cycle assessment (LCA) model of short-rotation willow biomass (*Salix* spp.) crops. *Bioenergy Res.* **2014**, *7*, 48–59. [CrossRef]
21. González-García, S.; Mola-Yudego, B.; Dimitriou, I.; Aronsson, P.; Murphy, R. Environmental assessment of energy production based on long term commercial willow plantations in Sweden. *Sci. Total Environ.* **2012**, *421*, 210–219. [CrossRef] [PubMed]
22. González-García, S.; Moreira, M.T.; Feijoo, G.; Murphy, R.J. Comparative life cycle assessment of ethanol production from fast-growing wood crops (black locust, eucalyptus and poplar). *Biomass Bioenergy* **2012**, *39*, 378–388. [CrossRef]

23. González-García, S.; Mola-Yudego, B.; Murphy, R.J. Life cycle assessment of potential energy uses for short rotation willow biomass in Sweden. *Int. J. Life Cycle Assess.* **2013**, *18*, 783–795. [CrossRef]
24. Krzyzaniak, M.; Stolarski, M.; Szczukowski, S.; Tworkowski, J. Life cycle assessment of willow produced in short rotation coppices for energy purposes. *J. Biobased Mater.* **2013**, *7*, 566–578. [CrossRef]
25. Thornley, P.; Gilbert, P.; Shackley, S.; Hammond, J. Maximizing the greenhouse gas reductions from biomass: The role of life cycle assessment. *Biomass Bioenergy* **2015**, *81*, 35–43. [CrossRef]
26. Morrison, B.; Golden, J.S. Southeastern united states wood pellets as a global energy resource: A cradle-to-gate life cycle assessment derived from empirical data. *Int. J. Sustain. Energy* **2018**, *37*, 134–146. [CrossRef]
27. Arteaga-Pérez, L.E.; Vega, M.; Rodríguez, L.C.; Flores, M.; Zaror, C.A.; Ledón, Y.C. Life-Cycle assessment of coal–biomass based electricity in Chile: Focus on using raw vs torrefied wood. *Energy Sustain. Dev.* **2015**, *29*, 81–90. [CrossRef]
28. Adams, P.W.R.; Shirley, J.E.J.; McManus, M.C. Comparative cradle-to-gate life cycle assessment of wood pellet production with torrefaction. *Appl. Energy* **2015**, *138*, 367–380. [CrossRef]
29. Garcia, D.P.; Caraschi, J.C.; Ventorim, G.; Vieira, F.H.A. Trends and challenges of Brazilian pellets industry originated from agroforestry. *Cerne* **2016**, *22*, 233–240. [CrossRef]
30. Röder, M.; Whittaker, C.; Thornley, P. How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues. *Biomass Bioenergy* **2015**, *79*, 50–63. [CrossRef]
31. Kabir, M.R.; Kumar, A. Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways. *Bioresour. Technol.* **2012**, *124*, 394–405. [CrossRef] [PubMed]
32. Laschi, A.; Marchi, E.; González-García, S. Environmental performance of wood pellets' production through life cycle analysis. *Energy* **2016**, *103*, 469–480. [CrossRef]
33. Morrison, B.; Golden, J.S. Life cycle assessment of co-firing coal and wood pellets in the southeastern united states. *J. Clean. Prod.* **2017**, *150*, 188–196. [CrossRef]
34. Hanssen, S.V.; Duden, A.S.; Junginger, M.; Dale, V.H.; van der Hilst, F.J.G.B. Wood pellets, what else? Greenhouse gas parity times of European electricity from wood pellets produced in the South-Eastern United States using different softwood feedstocks. *Gcb Bioenergy* **2017**, *9*, 1406–1422. [CrossRef]
35. Hoefnagels, R.; Resch, G.; Junginger, M.; Faaij, A. International and domestic uses of solid biofuels under different renewable energy support scenarios in the European union. *Appl. Energy* **2014**, *131*, 139–157. [CrossRef]
36. Ehrig, R.; Behrendt, F. Co-firing of imported wood pellets—An option to efficiently save CO_2 emissions in Europe? *Energy Policy* **2013**, *59*, 283–300. [CrossRef]
37. Dwivedi, P.; Khanna, M.; Bailis, R.; Ghilardi, A. Potential greenhouse gas benefits of transatlantic wood pellet trade. *Environ. Res. Lett.* **2014**, *9*, 024007. [CrossRef]
38. Wang, W.; Dwivedi, P.; Abt, R.; Khanna, M. Carbon savings with transatlantic trade in pellets: Accounting for market-driven effects. *Environ. Res. Lett.* **2015**, *10*, 114019. [CrossRef]
39. Eufrade Junior, H.D.J.; Melo, R.X.D.; Sartori, M.M.P.; Guerra, S.P.S.; Ballarin, A.W. Sustainable use of eucalypt biomass grown on short rotation coppice for bioenergy. *Biomass Bioenergy* **2016**, *90*, 15–21. [CrossRef]
40. Morales, M.; Aroca, G.; Rubilar, R.; Acuna, E.; Mola-Yudego, B.; González-García, S. Cradle-to-gate life cycle assessment of eucalyptus globulus short rotation plantations in Chile. *J. Clean. Prod.* **2015**, *99*, 239–249. [CrossRef]
41. Amaducci, S.; Facciotto, G.; Bergante, S.; Perego, A.; Serra, P.; Ferrarini, A.; Chimento, C. Biomass production and energy balance of herbaceous and woody crops on marginal soils in the Po valley. *Gcb Bioenergy* **2017**, *9*, 31–45. [CrossRef]
42. Goh, C.S.; Junginger, M.; Cocchi, M.; Marchal, D.; Thrän, D.; Hennig, C.; Heinimö, J.; Nikolaisen, L.; Schouwenberg, P.P.; Bradley, D. Wood pellet market and trade: A global perspective. *Biofuels Bioprod. Biorefin.* **2013**, *7*, 24–42. [CrossRef]
43. Bonsch, M.; Humpenöder, F.; Popp, A.; Bodirsky, B.; Dietrich, J.P.; Rolinski, S.; Biewald, A.; Lotze-Campen, H.; Weindl, I.; Gerten, D. Trade-offs between land and water requirements for large-scale bioenergy production. *Gcb Bioenergy* **2016**, *8*, 11–24. [CrossRef]
44. Jonker, J.G.G.; Junginger, M.; Faaij, A. Carbon payback period and carbon offset parity point of wood pellet production in the south-eastern united states. *Gcb Bioenergy* **2014**, *6*, 371–389. [CrossRef]

45. Guerra, S.P.; Garcia, E.A.; Lanças, K.P.; Rezende, M.A.; Spinelli, R. Heating value of eucalypt wood grown on SRC for energy production. *Fuel* **2014**, *137*, 360–363. [CrossRef]
46. Hellweg, S.; i Canals, L.M. Emerging approaches, challenges and opportunities in life cycle assessment. *Science* **2014**, *344*, 1109–1113. [CrossRef] [PubMed]
47. Guest, G.; Bright, R.M.; Cherubini, F.; Michelsen, O.; Strømman, A.H. Life cycle assessment of biomass-based combined heat and power plants: Centralized versus decentralized deployment strategies. *J. Ind. Ecol.* **2011**, *15*, 908–921. [CrossRef]
48. Oreggioni, G.D.; Singh, B.; Cherubini, F.; Guest, G.; Lausselet, C.; Luberti, M.; Ahn, H.; Strømman, A.H. Environmental assessment of biomass gasification combined heat and power plants with absorptive and adsorptive carbon capture units in Norway. *Int. J. Greenh. Gas Control* **2017**, *57*, 162–172. [CrossRef]
49. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. The ecoinvent database version 3 (part I): Overview and methodology. *Int. J. Life Cycle Assess.* **2016**, *21*, 1218–1230. [CrossRef]
50. PRé Consultants. *Simapro v8.1.1*; PRé Consultants: Amersfoort, The Netherlands, 2015.
51. Oers, L.V. *CML-IA–Database Containing Characterization Factors for Life Cycle Impact Assessment*, 2015 ed.; Centre of Environmental Science (CML), Leiden University: Leiden, The Netherlands, 2015; Available online: http://www.cml.leiden.edu/software/data-cmlia.html (accessed on 20 October 2018).
52. Rugani, B.; Golkowska, K.; Vázquez-Rowe, I.; Koster, D.; Benetto, E.; Verdonckt, P. Simulation of environmental impact scores within the life cycle of mixed wood chips from alternative short rotation coppice systems in Flanders (Belgium). *Appl. Energy* **2015**, *156*, 449–464. [CrossRef]
53. Dias, A.C.; Arroja, L. Environmental impacts of eucalypt and maritime pine wood production in Portugal. *J. Clean. Prod.* **2012**, *37*, 368–376. [CrossRef]
54. Guerra, S.P.S.; Oguri, G.; Spinelli, R. Harvesting eucalyptus energy plantations in Brazil with a modified New Holland forage harvester. *Biomass Bioenergy* **2016**, *86*, 21–27. [CrossRef]
55. Eufrade Junior, H.D.J.; Oguri, G.; de Melo, R.X.; Ballarin, A.W.; Guerra, S.P.S. Storage of whole-tree chips from high-density energy plantations of eucalyptus in Brazil. *Biomass Bioenergy* **2016**, *93*, 279–283. [CrossRef]
56. Whittaker, C.; Mortimer, N.; Murphy, R.; Matthews, R. Energy and greenhouse gas balance of the use of forest residues for bioenergy production in the UK. *Biomass Bioenergy* **2011**, *35*, 4581–4594. [CrossRef]
57. Forsberg, G. Biomass energy transport: Analysis of bioenergy transport chains using life cycle inventory method. *Biomass Bioenergy* **2000**, *19*, 17–30. [CrossRef]
58. Dias, A.C. Life cycle assessment of fuel chip production from eucalypt forest residues. *Int. J. Life Cycle Assess.* **2014**, *19*, 705–717. [CrossRef]
59. MarineTraffic. Voyage Planner. Available online: http://www.marinetraffic.com/ (accessed on 3 December 2017).
60. Oreggioni, G.D.; Brandani, S.; Luberti, M.; Baykan, Y.; Friedrich, D.; Ahn, H. CO_2 capture from syngas by an adsorption process at a biomass gasification CHP plant: Its comparison with amine-based CO_2 capture. *Int. J. Greenh. Gas Control* **2015**, *35*, 71–81. [CrossRef]
61. Weinberg, J.; Kaltschmitt, M. Life cycle assessment of mobility options using wood based fuels—Comparison of selected environmental effects and costs. *Bioresour. Technol.* **2013**, *150*, 420–428. [CrossRef] [PubMed]
62. Jungbluth, N.; Frischknecht, R.; Faist Emmenegger, M.; Steiner, R.; Tuchschmid, M. *Life Cycle Assessment of BTL-Fuel Production: Inventory Analysis*; ESU-services: Schaffhausen, Switzerland, 2007; Available online: http://www.renew-fuel.com/download.php?dl=del_sp5_wp2_5-2-7_07-07-30_esu.pdf&kat=16 (accessed on 20 October 2018).
63. Caduff, M.; Huijbregts, M.A.; Koehler, A.; Althaus, H.J.; Hellweg, S. Scaling relationships in life cycle assessment: The case of heat production from biomass and heat pumps. *J. Ind. Ecol.* **2014**, *18*, 393–406. [CrossRef]
64. Caduff, M.; Huijbregts, M.A.; Althaus, H.-J.; Koehler, A.; Hellweg, S. Wind power electricity: The bigger the turbine, the greener the electricity? *Environ. Sci. Technol.* **2012**, *46*, 4725–4733. [CrossRef] [PubMed]
65. Molino, A.; Chianese, S.; Musmarra, D. Biomass gasification technology: The state of the art overview. *J. Energy Chem.* **2016**, *25*, 10–25. [CrossRef]
66. Halland, E.; Mujezinovic, J.; Riis, F. *CO_2 Storage Atlas: Norwegian Continental Shelf*; Norwegian Petroleum Directorate: Stavanger, Norway, 2014.
67. Singh, B.; Strømman, A.H.; Hertwich, E.G. Comparative life cycle environmental assessment of CCS technologies. *Int. J. Greenh. Gas Control* **2011**, *5*, 911–921. [CrossRef]

68. Wildbolz, C. Life Cycle Assessment of Selected Technologies for CO_2 Transport and Sequestration. Ph.D. Thesis, Swiss Federal Institute of Technology Zurich, Zurich, Switzerland, 2007.
69. Koornneef, J.; van Keulen, T.; Faaij, A.; Turkenburg, W. Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO_2. *Int. J. Greenh. Gas Control* **2008**, *2*, 448–467. [CrossRef]
70. Câmara, G.; Soterroni, A.; Ramos, F.; Carvalho, A.; Andrade, P.; Souza, R.; Mosnier, A.; Mant, R.; Buurman, M.; Pena, M.; et al. *Modelling Land Use Change in Brazil: 2000–2050*; INPE, IPEA, IIASA, UNEP-WCMC: São José dos Campos, Brasília, Brazil; Laxenburg, Austria; Cambridge, UK, 2015.
71. De Oliveira Silva, R.; Barioni, L.G.; Hall, J.J.; Moretti, A.C.; Veloso, R.F.; Alexander, P.; Crespolini, M.; Moran, D. Sustainable intensification of Brazilian livestock production through optimized pasture restoration. *Agric. Syst.* **2017**, *153*, 201–211. [CrossRef]
72. Escobar, J.E.; Coelho, S.T.; Fritsche, U.R.; Iriarte, L. Perspectives for sustainable wood pellets production in Brazil. In Proceedings of the 22th European Biomass Conference, Hamburg, Germany, 23–26 June 2014; pp. 23–27.
73. Lapola, D.M.; Martinelli, L.A.; Peres, C.A.; Ometto, J.P.; Ferreira, M.E.; Nobre, C.A.; Aguiar, A.P.D.; Bustamante, M.M.; Cardoso, M.F.; Costa, M.H. Pervasive transition of the Brazilian land-use system. *Nat. Clim. Chang.* **2014**, *4*, 27. [CrossRef]
74. Sparovek, G.; Guidotti, V.; Pinto, L.F.G.; Berndes, G.; Barretto, A.; Cerignoni, F. Asymmetries of cattle and crop productivity and efficiency during Brazil's agricultural expansion from 1975 to 2006. *Elementa Sci. Anthopocene* **2018**, *6*, 25. [CrossRef]
75. Khatiwada, D.; Palmén, C.; Silveira, S. Evaluating the palm oil demand in Indonesia: Production trends, yields, and emerging issues. *Biofuels* **2018**, 1–13. [CrossRef]
76. IEA. *International Energy Agency, European Union-28: Electricity and Heat for 2014*; International Energy Agency: Paris, France, 2014; Available online: http://www.iea.org/statistics/statisticssearch/report/?year=2014&country=EU28&product=ElectricityandHeat (accessed on 20 October 2018).
77. Eurostat. *Energy Balance Sheets—2014 Data—2016 Edition*; Publications Office of the European Union: Luxembourg, 2016.
78. Le Quéré, C.; Andrew, R.M.; Canadell, J.G.; Sitch, S.; Korsbakken, J.I.; Peters, G.P.; Manning, A.C.; Boden, T.A.; Tans, P.P.; Houghton, R.A.; et al. Global carbon budget 2016. *Earth Syst. Sci. Data* **2016**, *8*, 605–649. [CrossRef]
79. Cava, M.G.; Pilon, N.A.; Ribeiro, M.C.; Durigan, G. Abandoned pastures cannot spontaneously recover the attributes of old-growth savannas. *J. Appl. Ecol.* **2018**, *55*, 1164–1172. [CrossRef]
80. Cohn, A.S.; Gil, J.; Berger, T.; Pellegrina, H.; Toledo, C. Patterns and processes of pasture to crop conversion in Brazil: Evidence from Mato Grosso State. *Land Use Policy* **2016**, *55*, 108–120. [CrossRef]
81. Ellison, D.; Morris, C.E.; Locatelli, B.; Sheil, D.; Cohen, J.; Murdiyarso, D.; Gutierrez, V.; Noordwijk, M.V.; Creed, I.F.; Pokorny, J.; et al. Trees, forests and water: Cool insights for a hot world. *Glob. Environ. Chang.* **2017**, *43*, 51–61. [CrossRef]
82. Smith, P.; Clark, H.; Dong, H.; Elsiddig, E.; Haberl, H.; Harper, R.; House, J.; Jafari, M.; Masera, O.; Mbow, C. *Agriculture, Forestry and Other Land Use (AFOLU)*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014.
83. Cook, R.L.; Binkley, D.; Stape, J.L. Eucalyptus plantation effects on soil carbon after 20 years and three rotations in Brazil. *For. Ecol. Manag.* **2016**, *359*, 92–98. [CrossRef]
84. Wolf, C.; Klein, D.; Weber-Blaschke, G.; Richter, K. Systematic review and meta-analysis of life cycle assessments for wood energy services. *J. Ind. Ecol.* **2016**, *20*, 743–763. [CrossRef]
85. Sunde, K.; Brekke, A.; Solberg, B. Environmental impacts and costs of woody Biomass-to-Liquid (BTL) production and use—A review. *For. Policy Econ.* **2011**, *13*, 591–602. [CrossRef]
86. IEA. *International Energy Agency, Technology Roadmap—Delivering Sustainable Bioenergy*; IEA: Paris, France, 2017.
87. Nunes, L.J.R.; Matias, J.C.O.; Catalão, J.P.S. A review on torrefied biomass pellets as a sustainable alternative to coal in power generation. *Renew. Sustain. Energy Rev.* **2014**, *40*, 153–160. [CrossRef]
88. Dos Santos, M.A.; Rosa, L.P.; Sikar, B.; Sikar, E.; dos Santos, E.O. Gross greenhouse gas fluxes from hydro-power reservoir compared to thermo-power plants. *Energy Policy* **2006**, *34*, 481–488. [CrossRef]

89. Levasseur, A.; Cavalett, O.; Fuglestvedt, J.S.; Gasser, T.; Johansson, D.J.; Jørgensen, S.V.; Raugei, M.; Reisinger, A.; Schivley, G.; Strømman, A. Enhancing life cycle impact assessment from climate science: Review of recent findings and recommendations for application to LCA. *Ecol. Indic.* **2016**, *71*, 163–174. [CrossRef]
90. Cherubini, F.; Fuglestvedt, J.; Gasser, T.; Reisinger, A.; Cavalett, O.; Huijbregts, M.A.; Johansson, D.J.; Jørgensen, S.V.; Raugei, M.; Schivley, G. Bridging the gap between impact assessment methods and climate science. *Environ. Sci. Policy* **2016**, *64*, 129–140. [CrossRef]
91. Pierrehumbert, R. Short-lived climate pollution. *Annu. Rev. Earth Planet. Sci.* **2014**, *42*, 341–379. [CrossRef]
92. Cherubini, F.; Bright, R.M.; Strømman, A.H. Site-specific global warming potentials of biogenic CO_2 for bioenergy: Contributions from carbon fluxes and albedo dynamics. *Environ. Res. Lett.* **2012**, *7*, 045902. [CrossRef]
93. Zhao, K.; Jackson, R.B. Biophysical forcings of land-use changes from potential forestry activities in North America. *Ecol. Monogr.* **2014**, *84*, 329–353. [CrossRef]
94. Cherubini, F.; Huijbregts, M.; Kindermann, G.; Van Zelm, R.; Van Der Velde, M.; Stadler, K.; Strømman, A.H. Global spatially explicit CO_2 emission metrics for forest bioenergy. *Sci. Rep.* **2016**, *6*, 20186. [CrossRef] [PubMed]
95. Breton, C.; Blanchet, P.; Amor, B.; Beauregard, R.; Chang, W.-S. Assessing the climate change impacts of biogenic carbon in buildings: A critical review of two main dynamic approaches. *Sustainability* **2018**, *10*, 2020. [CrossRef]
96. Shine, K.P.; Fuglestvedt, J.S.; Hailemariam, K.; Stuber, N. Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. *Clim. Chang.* **2005**, *68*, 281–302. [CrossRef]