Renewable and Sustainable Energy Reviews 118 (2020) 109506

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

Wood pellet supply chain costs – A review and cost optimization analysis

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ARTICLE INFO

Keywords:
Wood pellet price
Supply chain analysis
Techno-economic analysis
Cost optimization
Economies of scale
Biomass trade

ABSTRACT

Wood pellet-based electricity production has the potential to increasingly contribute to the achievement of climate targets. A reduction of supply chain costs could contribute to increased utilization of pellets. Existing literature on pellet costs was reviewed to explicate cost differences, focusing on the impact of supply chain design. This was combined with a techno-economic analysis of the impact of different design variables on cost components, including feedstock type, production location and pellet plant size. The results of this study show that variation in literature can only be partly attributed to design differences, with large remaining uncertainty. The cost reduction potential of optimization strategies was found to be limited. Different supply chain design approaches result in trade-offs between cost components. Increasing the size of pellet plants was calculated to result in decreased pelletizing and shipping costs, but at the same time leads to increased costs for feedstock procurement and transport. Supply chain costs are highly dependent on specific supply chain conditions, including the regional availability of feedstock, and results varied for different pellet plant locations analyzed within the US. The average calculated costs for a 500 kt/a pellet plant amount to 136 $€_{2017}$/t pellets, compared to 143 $€_{2017}$/t pellets for a 50 kt/a pellet plant. The most prominent components across the entire chain are feedstock costs and pelletizing operating costs, including additional feedstock use for drying. The data used in this study can be found in the supplementary database.

1. Introduction

Moving towards a low carbon future while maintaining economic growth requires the use of solid biomass for energy purposes. Co-firing of wood pellets in coal fired power plants can help provide a greener, less carbon-intensive, future while maintaining sufficient electricity generation capacity. One of the barriers to co-firing wood pellets is the significant price gap between coal and wood pellets, varying between 16 and 22 €/MWh[1,2], resulting in the reliance on subsidies [1,2]. At the price level of the second quarter of 2018, the required EU ETS price to break even would be 69 €/tonne[3] [3,4]. To lower supply chain costs, the impact of supply chain design variables, and underlying cost factors must be understood. There is little merit in focusing on lowering the costs of single supply chain components. All components react differently to changes, and optimization of some could have an opposite effect in others. Optimizations should be analyzed across the entire chain and for different conditions.

Various previous studies have explored wood pellet supply costs under different scenarios or conditions. The work by Obernberger and Thek [5] analyzed in great detail the costs of supply chain components and the total costs of producing pellets in Austria. Ehrig et al. [1] have analyzed the differences between pellet supply chain costs for pellets

Abbreviations: EU ETS, European Union Emissions Trading System; CF, Capacity factor; ETF, Empty trip factor; EF, Emission factor HFO; FC_{full}, fuel consumption at full load; $FC_{pellets}$, fuel consumption at the outward journey, fully loaded with pellets; FC_{empty}, fuel consumption of an empty ship; DWT, Deadweight tonnage; LWT, Lightweight tonnage; AT, Additional tonnage (fuel, water,stores, crew); FPL, Full pellet load, volume limited amount of pellets transported; SR, Stowage ratio cargo; $d_{pellets}$, Density pellets, at 10% moisture content; Ballast, Ballast at empty trip; MC, moisture content.

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[1] Corresponds to 8750 kt/a and 875 kt/a.

[2] Pellet spot prices ranged from 6.3 to 9.3 €/GJ, between 2009 and 2018, based on 17.5 GJ/tonne pellets [59,64]. Coal prices ranged from 1.9 €/GJ to 3.2 €/GJ between 2008 and 2018, based on 29.3 GJ/tonne coal [64,72].

[3] In the second quarter of 2018, the price difference between pellets and coal, as given by Argus Media, is 19 €/MWh [4]. When assuming a conversion efficiency of 48%, associated avoided CO_2 emission of 710 gCO_2/kWh and pellet supply chain GHG savings of 80% compared to coal, the required EU ETS price would be 69 €/ton [3].

https://doi.org/10.1016/j.rser.2019.109506
Received 6 June 2019; Received in revised form 4 October 2019; Accepted 18 October 2019
Available online 21 November 2019
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produced in three different countries and transported to Northwestern Europe, including use of different feedstock and different production scales. More recently, Boukherroub et al. [6] calculated the return on investment for pellet production and transport scenarios with various operating scales, level of government support, harvesting costs and sales price of pellets. Existing studies have resulted in more knowledge on specific case studies and supply chains. At the same time, existing studies show a large variation in results for several cost components. For instance, costs of biomass for pellet production varies almost a factor 4 in some examined literature studies. Costs of pelletizing, including capital and operational expenditures, varies more than a factor5.[4] These large cost ranges result in an uncertainty that hinders the use of literature studies for an assessment of wood pellet cost optimization strategies. What needs to be analyzed is whether these cost differences can be partly or fully explained by differences in the supply chain design, such as the type of feedstock used or the geographical scope. Increased knowledge on the impact of supply chain design factors on cost components will enable more realistic cost estimates for specific supply chains.

The objective of this study is first to improve understanding of the cost structure of inter-continental wood pellet supply chains and second to assess potential cost savings of individual components as well as the entire chain. The specific focus on inter-continental traded pellets is in line with the expectation that growing bioenergy consumption, combined with spatial distribution of biomass demand and supply, will result in increased trade of solid biomass [7]. In this study, the uncertainties of cost ranges in existing literature studies are analyzed, increasing the understanding of the source of variation. An explication of the impact of supply chain design variables on cost variation will increase knowledge and certainty on total supply chain costs of wood pellets. The first part of this work consists of an analysis of literature on total cost variation, assumptions made about supply chain design and the type of data used. This will highlight the costliest parts of the supply chain, which will be focused on in the second part of this study. In the second part, cost optimization strategies are analyzed, exploring the impact of supply chain variables on cost components. This study will pay particular attention to trade-offs or synergies between various cost components. Cost optimization must be analyzed from a supply chain perspective since supply chain design changes can have an opposite effect on different cost factors.

Researchers will benefit from the data analyzed in this study as it provides a good starting point for further research into supply chain optimization and provides insight into cost uncertainties and the impact of supply chain design on total costs. This article is supplemented by a harmonized and up-to-date dataset of supply chain costs of different components, to be used by the scientific community in future work. Furthermore, this research will be especially relevant for policy support. The quantification of the total costs of producing and transporting pellets can be used to determine required subsidy levels to support the replacement of fossil fuels for wood pellets.

2. Method

This article consists of a literature review of studies that have researched wood pellet supply chain costs, focused on explicating the difference between costs in literature. Input data as well as supply chain design assumptions were compiled in an excel database, which is made available with this article. This literature review was used, combined with additional data, as input for a techno-economic assessment of the impact of supply chain design and cost optimization strategies.

[4] Feedstock costs are 27 €/t of pellets for a mixture of sawdust and shavings in Mobini et al. [28], and 114 $/t pellets for roundwood in McKechnie et al. [44]. Total costs of pelletizing in Agar [39] is 25 €/t pellets, compared to 136 €/t in Pirraglia et al. [33].

2.1. Supply chain scope

The supply chain considered in this article is the typical chain of wood pellets used to replace solid fossil fuels in large scale utilities. This chain includes large scale production of pellets, with international and intermodal transport to import regions. Pellet production from agricultural feedstocks is not considered. The few large-scale power plants in Western Europe that consume pellets are currently only using forestry-based pellets, which are considered technically superior and easier to combust in existing boilers [8]. The different supply chain components included in this study are shown in Fig. 1, together with the most important considerations and assumptions.

2.2. Geographical scope

Literature analyzed in this study is based on a geographical scope of production of pellets in various world regions and consumption in Western Europe, imported through the ARA ports (Amsterdam-Rotterdam-Antwerp). The impact of supply chain design will be analyzed and calculated in more detail, applied to a specific supply chain of pellet production in the southeastern part of the United States (SE US) and consumption in the Netherlands. The United States pellet market is the most developed in the world, with pellets for export being produced mainly in the southeast. The trade between the SE US and Europe totaled 6.7 Mt in 2017, making it the largest wood pellet trade flow in the world [9,10].

2.3. Difference between cost and price

The difference between the definitions of cost and price is whether a profit margin is included. Literature studies referenced in this study generally use the phrase “cost”, even for components in which profit seems to be included such as logistics cost based on price quotes of logistical companies. The difference between cost and price also depends on the perspective of actors within the chain. For instance, the price of feedstock includes profit for land owners, but is at the same time a cost expense for pellet producers. Literature studies often use different approaches, mixing cost and price data. In most cases it is not clear whether sources refer to costs or prices, or what profit margins are included. Cost data from literature used in various parts of this paper are used as such, without adding or removing profit margins for certain components.

For the calculations made in this study, profit margins are excluded as much as possible to calculate the lowest possible supply chain costs. This is specifically the case for calculated pellet production and road transport costs. Data limitations result in the use of price data for some calculated components, such as the use of charter rates in the calculation of rail transport costs and shipping costs, and the use of data on feedstock prices paid by pellet producers.

2.4. Supply chain variables and components

The impact of supply chain design variables and context factors will be analyzed separately. The remainder of this article will focus on the impact of four different supply chain design variables: Production country, site location, pellet plant size and feedstock type. The methodology and results of the impact of context factors can be found in Appendix A. Context variables analyzed are shipping charter rates and fuel costs and the differences in exchange rates and inflation. For all combinations of supply chain design variables and factors, an evaluation was made of the impact on cost components. This evaluation was based on a first screening of literature and an initial assessment rooted in previous work and experience. The different supply chain components analyzed in this research are: 1. Feedstock cost, delivered to pellet plant, 2. Pelletizing cost, 3. Costs of transport to export port, 4. Handling & storage costs at export port, 5. International transport costs (usually

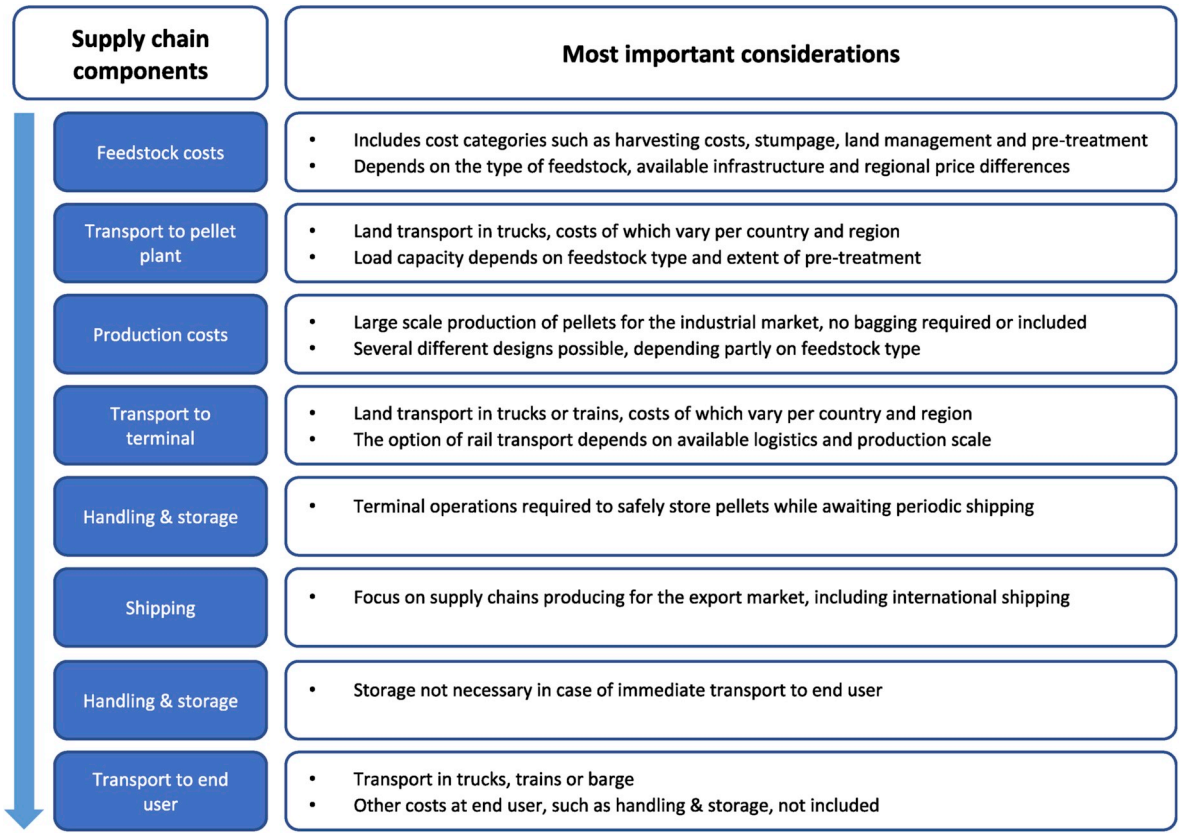

Fig. 1. Supply chain components included in this study.

shipping cost), 6. Costs of handling & storage at import port. The focus will be on combinations of variables and components with the strongest impacts, as shown in Table 1.

The uncertainty in pelletizing costs is analyzed in more detail by assessing the variability within three different types of pellet production expenses. Building a pellet plant requires upfront capital costs, usually secured in the form of outside investments or loans. Amortization of this capital results in expenses during the operation of the pellet plant. Capital costs are divided into two categories, which are expected to respond differently to supply chain design: Capital costs related to equipment for pellet production and storage, and capital costs for peripheral equipment, infrastructure, planning, installation and construction. The third category is the operating costs required to produce pellets with the installed equipment, consisting of costs of feedstock transported to pellet plants, labor costs and costs for heat and electricity.

Since most studies do not specify the energy content of pellets, costs are given per tonne of produced pellets instead. If supply chain components were not included in specific literatures studies, the average of all other data points were used. Costs were first accounted for inflation until 2017, according to equation (1). and subsequently converted to euro values where necessary [11,12]. For literature sources that did not explicitly include a reference year for costs data, the submission year, or else the publication year was used to calculate the inflation adjusted values.

$$Adjusted\ value = \left(Literature\ Value / Consumer\ Price\ Index \right) 100 \quad (1)$$

2.5. Input data

2.5.1. Selection of literature

The basis for the selection of literature in this work was a focused search in Scopus and ScienceDirect for all the articles between 2007 and 2017 containing the words (wood) pellet(s) and any term related to supply chain costs.[5] After an initial screening of titles and abstracts, 57 studies were assessed for suitability based on three criteria, starting with the type of feedstock used to produce pellets. There are considerable differences between pelletizing forestry residues and agricultural residues, both in terms of feedstock costs and pelletizing process [13]. The size of a pellet plant has an impact on the supply chain design. The second criterium was the size of analyzed pellet plants. Pellet plants producing for the export market in the SE US range between production sizes of 12 kt/a to 825 kt/a [14]. In this research, only studies on pellet plants >12 kt/a were included. In case the pellet plant size was not explicitly mentioned in a literature study, an assumption was made based on the available costs data. For instance, studies that include costs for long distance feedstock sourcing or intermodal pellet transportation were assumed to be based on larger scale pellet plants and were included in the analyses. Explicit information on costs parameters is required to compare studies with different scopes and assumptions. Only studies that provide information on different costs components or parameters were considered suitable to include in the analysis. The final criterium was data availability. Only studies that explicitly include data on the calculation of supply chain costs, for a minimum of three cost components, were considered suitable input to conduct a techno-economic analysis. Additional literature was identified by consulting the bibliographies of already included studies.

The final list of included literature was used to analyze the type of cost data used and the variation of cost results. The results of this analysis consist of a general description of the literature, including the geographical scope, type of feedstock used, production size, publication

[5] supply chain/supply chain costs/costs/net present value/cash flow/rate of return/value chain/economics/economic assessment/economic analysis/financial analysis.

Table 1
Impact of supply chain design variables on cost components, dark yellow = strong impact, light yellow = weak impact. White = no/very little impact and therefore excluded from the analysis.

	Feedstock		Feedstock transport		CAPEX		OPEX				Transport to port		Shipping		
Variables \ **Factors**	Feedstock costs		Feedstock transport distance	Specific transport costs	Required equipment	Specific equipment costs	Required labor	Specific labor costs	Required processing energy	Utilities costs	Pellets transport distance	Availability of rail infrastructure	Shipping distance	Availability of ship sizes	Specific shipping costs
Feedstock															
Country															
Site location															
Scale															

year and included costs components. The type of input data used in the different literature studies was analyzed qualitatively. Distinct types of data sources were identified: *Expert judgment*, *industry data*, publicly available *market data*, *literature sources* and *unknown sources*. Literature sources were further divided into categories to show the age of cited literature, ranging from *literature before 2000*, to *literature before 2020*. *Self-citation* is included as the final category of literature sources. Links between the included studies are shown explicitly by analyzing the citations between the include group of studies.

2.5.2. Calculation of transport costs

Road and rail transport costs were calculated using a GIS-based transport model which was developed for this analysis. The model was based on existing infrastructure networks in the United States. Transport distances were calculated based on Railroads maps and OpenStreetMap, as made available by Esri [15] and Geofabrik [16]. Costs were calculated using the parameters given in table B1 in Appendix B. The assumption was made that truck drivers are generally paid per 12-h shift, making as many deliveries as possible within this time period. Unused paid hours were added to the trip costs. On short distances, truck transport is the cheapest and most flexible, benefitting from low capital costs. The much larger capacity of rail transport results in lower variable costs, ensuring lower overall costs for long distance transport, but requires proximity of railways. Rail transport is included as a feasible option for pellet plants within 20 km of existing railroads. Freight is not transferred from road to rail infrastructure or between different railroad companies. Transport costs were calculated to a few selected ports currently exporting wood pellets from the SE US,[6] from which the cheapest option was selected [17].

Shipping costs were calculated between the ports of Savannah and Rotterdam as consisting of two components, time-related charter costs and fuel consumption costs, for Handysize and Supramax ships. Costs were analyzed for a longer time period to analyze the impact of cost fluctuations, using yearly average charter costs and fuel costs [18]. For the period in which data on maritime fuel costs was not available, before 2009, costs were modelled after the crude oil price [19,20]. Detailed methodology on the calculation of shipping costs can be found in Appendix B, using the parameters given in Table B.2.

2.6. Supply chain design variables

2.6.1. Feedstock type

Wood pellets can be produced from several types of forestry feedstocks, from industry residues, forestry management residues or pulp- or timber grade pulpwood.[7] Large scale pellet production will often be designed based on a mixture of various feedstocks, depending on local availability and costs. Besides potential price differences between feedstock types, pelletizing costs are affected as well. The necessity of including various size reduction and moisture reduction steps in the pelletizing process depends on the raw material used, as indicated in Fig. 2, Table D.1.

Variation in literature of feedstock costs and pelletizing costs for different feedstocks was quantified through a Monte Carlo analysis. It was not considered possible to assess the likelihood of individual data points from literature, instead trendlines, choosing between linear, power, exponential and logarithmic functions, were fitted to literature values using Microsoft Excel. The trend line with the best fit, with the highest R-squared value, was used to model probability distributions for each feedstock category. These distributions, confined between the lowest and highest literature data points, were used as input for Monte Carlo simulations. After 100,000 simulations, the resulting probability distributions were used to calculate average values as well as 50% likelihood values for each specific feedstock.

The uncertainty of probability distributions depends strongly on the

[6] Baton Rouge, Mobile, Norfolk, Panama City, Savannah.

[7] Pulpwood refers to trees or parts of trees from plantation forests that are of too low quality to produce lumber. This category consists of low grade roundwood (for instance damaged or crooked trees), tree tops left as by-product of sawtimber harvest as well as commercial thinnings.

[8] Moisture content based on several included literature studies, as shown in Appendix D. Net calorific value based on [22]. Feedstock is assumed to be dried to 8% before pelletization. The energy requirement per t of evaporated water, ER, was assumed to be 1200 kWh/t [5], produced in a chips boiler with efficiency, ηcb, of 85% [23].

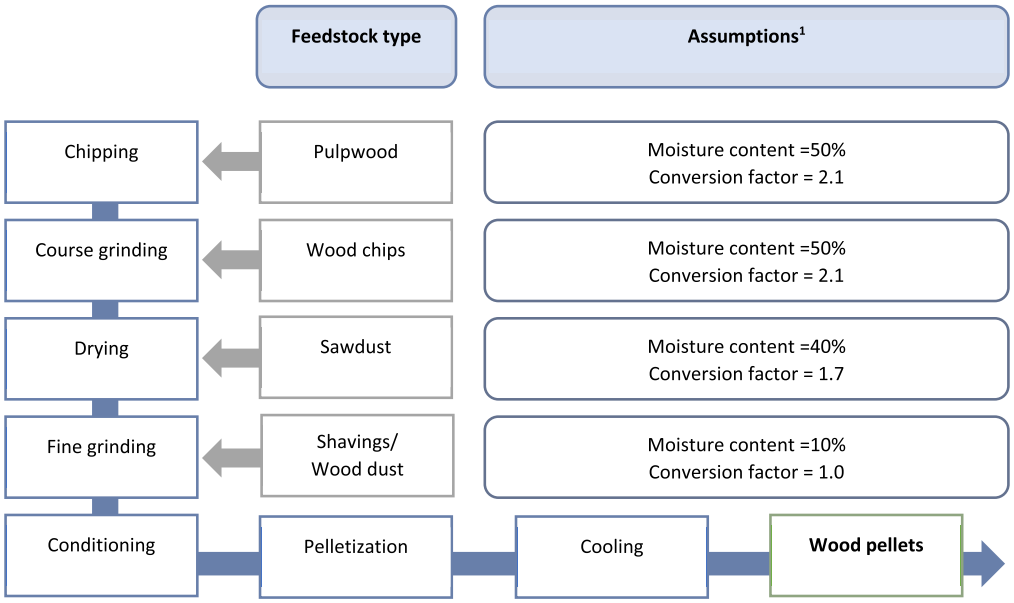

Fig. 2. Overview of pelletization steps, for different feedstock types.[8]

number of data points available as input. Monte Carlo analysis was only considered suitable for feedstock costs, and not for other cost components, because of the relatively large availability of data in included literature. Only the feedstock categories for which there was enough data, from at least five different studies, were separately included. This resulted in the categories *Pulpwood, Sawdust* and the combination of *Sawdust/shavings*. In this analysis, both the variation in feedstock costs and the pelletizing costs for different feedstocks were included.

Feedstock costs are verified with market data from the United States [21]. Costs for respectively pulpwood and sawmill residuals were taken from the United States Energy Information Administration (US EIA). The US EIA requires all pellet producers in the US to report information on the type of feedstock used and the price paid. The feedstock categories used by the US EIA only partially match feedstock assumptions from literature studies. For this study, US EIA data on Roundwood/pulpwood was used for pulpwood calculations, data on Sawmill residuals was used for sawdust calculations. US EIA data and the average exchange rates used can be found in table Table C.1 in Appendix C. Other feedstock categories could not be assessed. US EIA cost data is only available for raw material, without information on the moisture content of feedstock types. Conversion factors were calculated as in equation (2)., using variables and assumptions as shown in Fig. 2.

$$Conversion\ factor = \frac{(1 - MC_{out})}{(1 - MC_{in})} + \frac{(MC_{in} - MC_{out})*ER}{\eta_{cb}} \times \frac{1}{NCV} \quad (2)$$

2.6.2. Production country

Several cost factors are expected to vary between different pellet production countries, such as feedstock costs, labor costs, fuel costs and availability of infrastructure. The analysis of country impact will focus on factors explicitly included in several literature studies, namely feedstock costs and shipping costs. Cost variation of feedstock in several countries was analyzed in the same way as the different feedstock types. A Monte Carlo analysis was done for the countries for which enough data was available, which were *the United States* and *Canada*. There were not enough data points to use Monte Carlo analyses for the other cost components analyzed for country related cost differences.

Shipping costs are directly affected by the geographical scope since the distance between production and consumption country largely determines shipping costs. To analyze the impact of shipping distance, costs from literature were normalized by assuming a linear cost increase per distance. Shipping distance was taken directly from literature studies when explicitly mentioned. In case this information was not included, distances were assumed based on the general geographical scope.[9] The impact of geographical scope on utility costs is assumed to be significant. Factors such as local taxes, and subsidies, as well as costs for labor, fuel and electricity all depend on the country and specific region of production. However, because of the complexity of these factors, combined with time and resource limitations, the impact of the pellet production country on utility costs was not included in the final analysis.

2.6.3. Wood pellet plant site selection

One of the most important factors in choosing a suitable pellet production site is the availability of feedstock. This aspect not only impacts the price of feedstock but also the costs of transporting feedstock to the pellet plant. Since transparent data on regional price variations of feedstock is not available, the focus of this article will be on the impact of supply of biomass on feedstock transportation costs. This was analyzed by calculating feedstock transport costs for pellet plants of the same size, on different locations. To produce more results as realistic as possible, the location of existing pellet plants in the SE US were used in this analysis. A list of the pellet plants in the SE US producing pellets for the export market at the time of this analysis can be found in Appendix E. These plants are presumably located in fiber baskets with enough biomass to support a pellet plant. Feedstock supply areas were calculated based on local biomass availability on county level in the SE US, taken from Fingerman et al. [24], calculating transport costs from weighted centers of counties. Biomass was allocated starting from the county and pellet plant combination with the lowest transport costs, allowing for partial allocation in any case where supply exceeded remaining demand of a pellet plant. By following this method, the impact of competing pellet plants on regional feedstock availability is included. The allocation model was explicitly designed to optimize for single feedstock deliveries as opposed to a system optimization of lowest costs to all pellet plants. Optimizing for the entire system is considered less realistic since most pellet plants operate independently and will compete for feedstock with neighboring plants. A pellet plant's location

[9] Assumed distance to the ARA region: West Canada – 16,500 km; East Canada – 5000 km; Ontario, Canada – 6500 km; St. Petersburg, Russia – 2900 km; Cape town, South Africa – 13,500 km.

will also impact transportation of pellets to export terminals, since site selection will determine the transportation distance to the nearest suitable port. This was analyzed by comparing the transportation costs from pellet plants to the export ports included in this study [17].

2.6.4. Pellet plant size

Different supply chain components react different to scale increases. Feedstock costs are assumed to be relatively constant with increasing scale, provided that sufficient feedstock is available. Feedstock supply areas, and therefore feedstock transportation costs, will presumably increase with increased pellet plant size. To illustrate this, the impact of pellet plant size on transportation costs was calculated. To explore the impact of pellet plant size, the aforementioned transportation model was run three times, once for the actual size of existing pellet plants and for a small and large pellet plant with assumed sizes of 50 and 500 kt/a production size.

Rail transport requires the transportation of a minimum quantity of pellets. Using train transport is considerably more cost effective when using a unit train, consisting of 40–120 railcars, delivering according to a contracted schedule [25]. According to Obernberger and Thek [5], storage silos at pellet plants generally hold about 8 days of production. The assumption was made that pellets need to be distributed from pellet plants once a week, during 90% of the year, resulting in a minimum of 168 kt/a for a 40-year car train. The same rational was applied to ship size, assuming pellets need to be shipped out once a month. Cost-effective shipping depends on carrying as much load as possible, therefore the assumption was made that larger ships will only be used if the amount of cargo approaches the maximum tonnage. Twelve shipments of a fully loaded Supramax ship would result in the transportation of 580 kt/a [26]. Based on these calculations the assumption was made that rail transport and the use of Supramax ships are viable options for the large pellet plant but not for the small pellet plant.

Pelletizing capital and operational expenditures are expected to decrease with increasing size. Wood pellets are produced in modular designed pellet mills with several parallel production lines. For example, a pellet plants producing 600 kt/a could consist of four parallel production lines, with five pellet mills per line [27,28]. Although this modular design limits the scale up of equipment, buyers of pellet equipment expect volume discount when buying multiple equipment units, resulting in decreased equipment costs [29]. With increasing pellet production capacity, the required processing labor per unit of output is assumed to decrease to a large extent. Pellet production is a highly automated process, the number of production workers to monitor processes will not increase linearly with production capacity. Furthermore, administrative personnel requirements will not change considerably with larger production output.

A general economies of scale factor of 0.85 was used in consultation with pellet production experts. Scaling factors assumed in literature vary between 0.7 [30–33] and 0.82 [5]. The labor component of OPEX costs are considered to scale much more significantly, with an assumed scale factor of 0.25 [34]. Other operational expenditures, such as the costs of electricity and heat are not considered to scale at all. Capital expenditures and operational expenditures of different sized pellet plants were analyzed by applying a scale factor to costs from literature. For the reference pellet plant, 50 kt/a production was assumed. The literature studies on pellet plants with sizes below 100 kt/a were considered representative. Average costs from these studies were used for assumptions on capital expenditures, labor costs and other operational expenditures. Costs were indexed based on the pellet plant size, using the same economies of scale factors.

2.7. Total supply chain costs

Based on the analyses in this study, the total supply chain costs for two different types of pellet plants were calculated. The first type of pellet plant assumed is a small, 50 kt/a plant using sawmill residues. The second is a larger, 500 kt/a pellet plant using pulpwood and having access to rail infrastructure. Furthermore, the assumption was made that the small plant will use Handysize ships to transport pellets overseas, whereas the large pellet plant uses Supramax ships. Besides the difference in feedstock costs, the additional equipment required for drying and grinding of pulpwood compared to sawmill residues is also included in the total cost overview. This is analyzed by either fully including or excluding the costs of grinding and drying equipment, based on investment cost data as given in some of the included literature studies [5,28,33,35–37]. These costs were amortized assuming a debt repayment period of 10 years and a cost of debt of 7% [38]. The differences in electricity and heat requirement were not assessed in detail but would contribute to slightly higher operating costs for using pulpwood instead of residues.

3. Results

3.1. Literature review

3.1.1. Selection of literature

Applying the selection criteria resulted in the selection of 23 studies for further analysis. Details on scope and design can be found in Table 2, Table F.1. Some of the included studies are aimed at analyzing costs of bagged pellets, torrefied wood pellets, chips or other forestry biomass. These studies were considered to provide useful data on some supply chain components that match the scope of this study, such as the costs of forestry feedstock collection and transport.

The data set is comprised of a few early publications, five in total, from the years 2004–2006. In 2010, corresponding to a sharp increase in pellet production in the United States for export to Europe, the topic appears to be under renewed interest [40]. Eleven studies published in the years 2010–2013 are included. In the more recent studies, from 2014 to 2017, there is slightly more focus on additional pre-treatment technologies, such as the production of torrefied pellets [39,41–46], and on use of alternative feedstock such as damaged pulpwood and thinnings [6,47].

The size of pellet plants assumed in the different literature studies varies between 24 and 200 kt/a of pellet production. The assumed size of pellet plants was smaller in the studies published until 2010 than in later years, as shown in Fig. 3 [48,49]. This is still significantly smaller than some of the actual pellet plants in the US, especially the plants producing pellets for the export market which average at 389 kt/a [14]. In the United States, the total production capacity in 2000 measured 460 kt/a, produced in small scale production units below 50 kt/a capacity [50]. From 2008 onwards, several significantly larger pellet plants with annual output of >500 kt/a have started to produce pellets in the Southeast region of the US [9,17]. The misrepresentation of pellet plant size in literature could impact the certainty of cost estimates.

As shown in Fig. 4, all studies at least include the costs of feedstock. In some cases, the feedstock costs are given as delivered to the pellet plant whereas in other studies a distinction is made between transport costs and purchasing costs of feedstock from the perspective of a pellet producer. A few authors, such as Svanberg et al. [46], Lu et al. [52] and Boukherroub et al. [6] include further details on timber harvesting operations, such as harvesting costs, collection costs and stumpage fees. With the exception of the studies by Pirraglia et al. [45] and Svanberg et al. [46], all studies include pelletizing costs. Some studies include a large level of detail such as Thek & Obernberger [38], Obernberger & Thek [5] and Mobini et al. [28] whereas other studies only give the total costs of pelletizing [43,52,53]. Transport to export ports and shipping costs are covered in more than half of the studies while handling & storage costs in export and imports ports are covered in about a third of the studies. Some studies include regional distribution of pellets, analyzing pellet production and consumption within the same country [5,38,44]. Considering the differences between regional distribution and long-distance bulk transport, these costs estimates are left out of this

Table 2
Overview of literature sources included in this study.

Abbreviations			
Production country		Feedstock type	Product type
Netherlands- NL	South Africa – ZA	Pulpwood – 1	White wood pellets – 1
Europe – EUR	Australia – AU	Damaged pulpwood – 2	Torrefied wood pellets – 2
United States - US	Russia – RU	Thinnings – 3	Chips – 3
Canada – CA	Argentina – AR	Sawdust – 4	
Austria – AT	Finland – FI	Shavings – 5	
Sweden – SE	Germany – DE		
Belgium – BE	Norway – NO		

Source[a]	Production region	Consumption region	International transport	Feedstock type	Size (kt/a)	Product type
1	AT/SE	AT/SE	No	4	24/80	1
2	ZA	EUR	Yes	1, 4	56/80	1,2
3	CA	EUR	Yes	4, 5	32	1
4	CA	–	No	4	45	1
5	CA	NL/SE	Yes	4	100	1
6	AT	AT	No	4	40	1
7	US	US	No	1	75	1
8	CA	NL/SE	Yes	–	180	1,2
9	US	NL	Yes	4, 5	150	1
10	CA	EUR	Yes	1, 4, 5	–	1
11	AR	–	No	4, 5	24	1
12	CA	EUR/CA	Yes	4, 5	160	1
13	US	US	No	1	100	2
14	US	NL/BE	Yes	1	75	1
15	SE	SE	No	1	200	2
16	FI/DE/NO/SE/US	EUR	Yes	1, 4, 5	120	1
17	CA/AU/RU	NL	Yes	1, 4, 5	40/120	1
18	CA	EUR/CA	Yes	4, 5	160	2
19	US	US	No	1	–	1
20	CA	CA	No	1	150	1,2
21	CA	NL	Yes	2	–	1,3
22	CA	NL	Yes	2, 3	50/100/150	1
23	No specific country[b]		Yes	–	64/80	1,2

[a] Literature reference numbers can be found in Appendix F.
[b] Cost data corresponds to market rates in the Netherlands, a port-to-port shipping distance is included, roughly the distance from South-Africa to the Netherlands or Brazil to Finland [39].

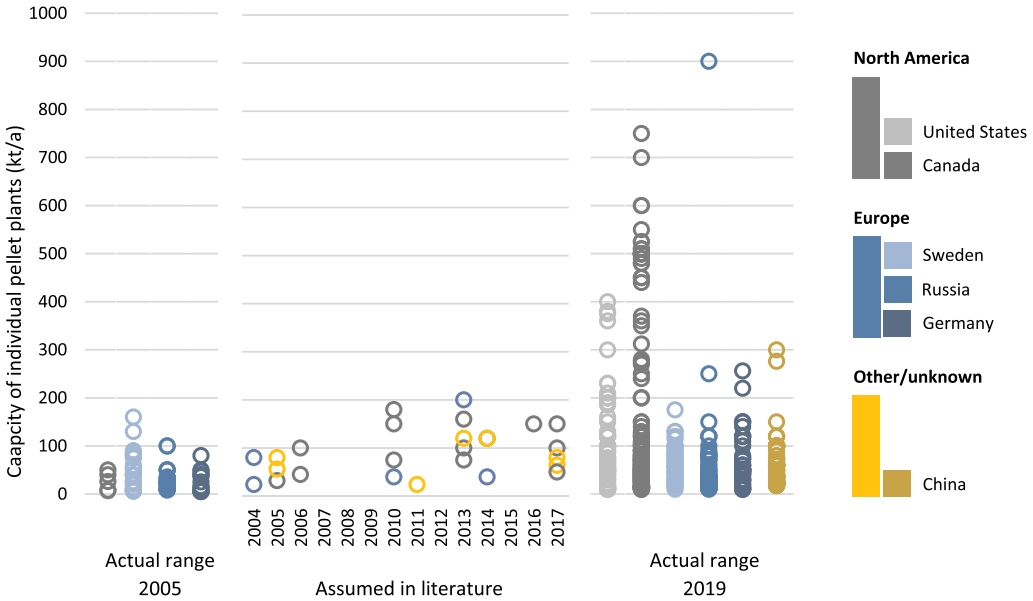

Fig. 3. –Pellet plant sizes assumed in analyzed literature and actual size ranges of existing pellet plants in different countries in 2005 and 2019 [48,51].

review. Transport in import countries is included in five studies, four of which analyze transport costs in the Netherlands and one of which analyses costs in the United Kingdom [1,39,41,54,55].

There are considerable differences between the type of input data used in the literature studies under review. Some studies make use of industry data such as data from pellet plants or logistical companies. This is most notable in Bergman [41], Mobini et al. [28], Mobini et al. [42] and Boukherroub et al. [6]. This use of data based on operational

Fig. 4. Type of data referenced in the analyzed literature.

information could increase the data reliability of these studies. On the other hand, this data is often used without providing further details on the supply chain design or assumptions associated with this data. This increases the uncertainty and limits the replicability of these studies. Besides the use of data from industry partners, several studies make use of assessments of experts, such as Hoque et al. [56] and Mobini et al. [42]. A few studies make statements on supply chain costs components without further clarification or have an incomplete bibliography. This makes it very difficult to assess the usefulness and reliability of data from these sources.

An issues with the included literature sources is that similar values are often the result of having used the same data source, as illustrated in Fig. 5. A group of original sources from 2004 to 2006 are used as input in most of the literature in later years. Articles written between 2010 and 2013 are partially based on those first few studies. At the same time these articles are used as input for a third group of papers, written between 2013 and 2017. Indirectly, some of the newest studies refer to data which stems from the earliest articles. These secondary citations hide potential issues with the original data and often do not account for the specific framing of data in the original studies.

The problem with re-use of data is twofold. First of all there is the issue of uncertainty. In case of similar costs values, a conclusion is easily made that there is a strong consensus in literature, whereas this could be the result of repeating use of the same input data. Another issue is the fact that studies from 2004 to 2006 most likely contain outdated information. For instance, the costs of shipping, handling and storage in Mobini et al. [42] are taken from a combination of sources, among which a source from 2002. Cost data on wood pellet production, and several transport and handling steps in Agar [39], was taken from a source dated back to 2005. This data appears to be used without price level accounting to adjust for inflation. As was explained in section 2.4, the data in this study was adjusted to 2017 euros. For several cost factors, such as pelletizing and shipping costs, the use of outdated data could result in a misrepresentation of the actual situation, even if inflation is accounted for. Shipping costs have fluctuated strongly with

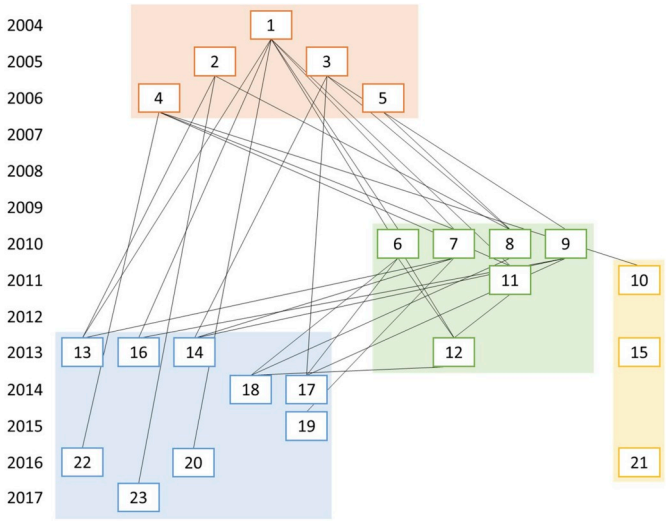

Fig. 5. Data linkages between the included literature studies. Numbers refer to literature reference numbers, as referred to in Table 2, and given in Appendix F.

changing market conditions since the first published study in 2004. The pellet market has changed drastically in this period, for instance when considering the size of pellet plants or the type of feedstock used, transitioning from the use of excess mill residues to predominant use of softwood pulpwood [57]. These changes will have had an impact on cost factors of pellet production.

3.1.2. Variation in cost components

The total supply chain costs in the included literature, including averages for supply chain components not included in studies, range between 88 €/t and 279 €/t with an average of 163 €/t and median value of 153 €/t (Fig. 6). The variation for individual cost components is large,

as can be seen in Fig. 7. The costs of transporting pellets to export harbors range between 1 €/t and 29 €/t. The variation is also large for the costs of pelletizing (factor 10 difference), delivered feedstock to pellet plants (factor 9 difference), for handling and storage in export ports (factor 8 difference) and for shipping (factor 6 difference). When comparing the different components of pelletizing costs, the operating costs stand out. This component makes up the largest, and most uncertain, part of the pelletizing costs. Pellet equipment is produced and traded globally, and economies of scale impact equipment cost to a lesser extent compared to some operating cost factors such as labor cost. Some of the components in operating cost, such as the cost of feedstock or transport, are likely impacted to a large extent by supply chain design. It must be noted that the sum of the capital and operating costs differs from the total pelletizing costs shown in Fig. 7. This is because total costs are based on a larger set of data points, including also the studies that only provide data on total pelletizing costs and not on cost components.

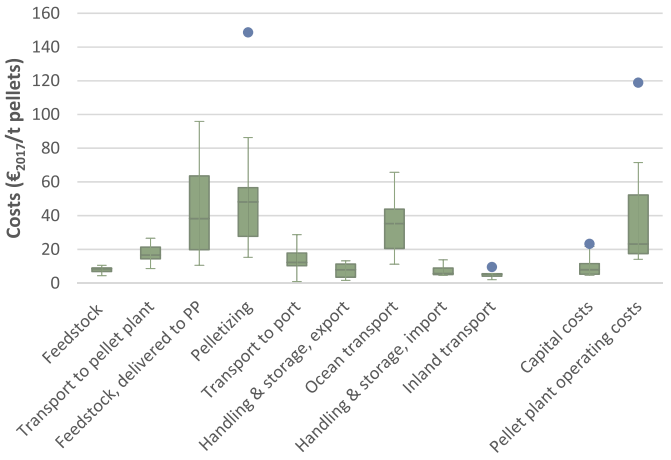

Fig. 7. Boxplot of cost values of different supply chain components in analyzed literature, including minimum, median and maximum values and cost ranges between the 1st and 3rd quantile. Blue dots represent outlier data points. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Supply chain design variables

3.2.1. Feedstock type

In the analyzed literature, the average feedstock costs of a combination of sawdust and shavings is the least expensive, followed by sawdust. The use of pulpwood results in the highest supply chain costs, as can be seen in Table 3. Pelletizing cost for sawdust/shavings are also lower than pelletizing cost for the pulpwood combination. Running the Monte Carlo analysis results in average total supply chain costs of 124 €/t pellets for sawdust/shavings pellets, followed by sawdust, with an average of 137 €/t pellets, as shown in Fig. 8. Pulpwood pellets are the most, averaging at 153 €/t pellets respectively. When comparing the 50% likelihood ranges, the total costs for pellets from sawdust/shavings are clearly below the values for the pulpwood-based pellets. Costs of sawdust/shavings pellets overlap with the two other categories. The additional capital required at a large-scale pellet plant for the processing of pulpwood adds 2.7 €/t. This is most likely an underestimation since this does not include installation of equipment or operational expenditures such as personnel and maintenance costs.

Data on feedstock prices paid by pellet producers in the United States shows a smaller difference between pulpwood and sawmill residues. When comparing the costs as given, in $/t feedstock, over 2017 and 2018 there is no difference between the two feedstock types, both averaging at 29 $/t. The impact of variation exchange rates in the respective months introduces a small difference, with pulpwood being slightly cheaper at 26 €/t feedstock compared to 27 €/t feedstock for sawmill residues. Applying the different conversion efficiencies based different assumed moisture contents, the costs of sawmill residues amount to 46 €/t pellets, compared to 54 €/t for pulpwood. This conversion relies heavily on the assumed moisture content of feedstock. The impact of these assumptions is shortly discussed in section 3.4. The moisture contents assumed in the literature studies also vary to a considerable extent, even for similar feedstock types, as can be seen in Appendix G (Figure G.1).

Table 3
Feedstock and pelletizing cost for different feedstock types, in €2017/t pellets, as calculated based on a Monte Carlo analysis of cost data from literature.

	Average value			50% likelihood range
	Feedstock cost	Pelletizing cost	Total	Total
Sawdust/ shavings	23.3	32.0	124.1	111–138
Sawdust	27.8	39.7	136.6	115–158
Pulpwood	37.4	46.0	152.5	129–175

3.2.2. Production country

For the two different countries included in the Monte Carlo analysis, the United States and Canada, there is a small difference in the feedstock cost in literature, as shown in Fig. 9 and Table 4. Feedstock cost in the

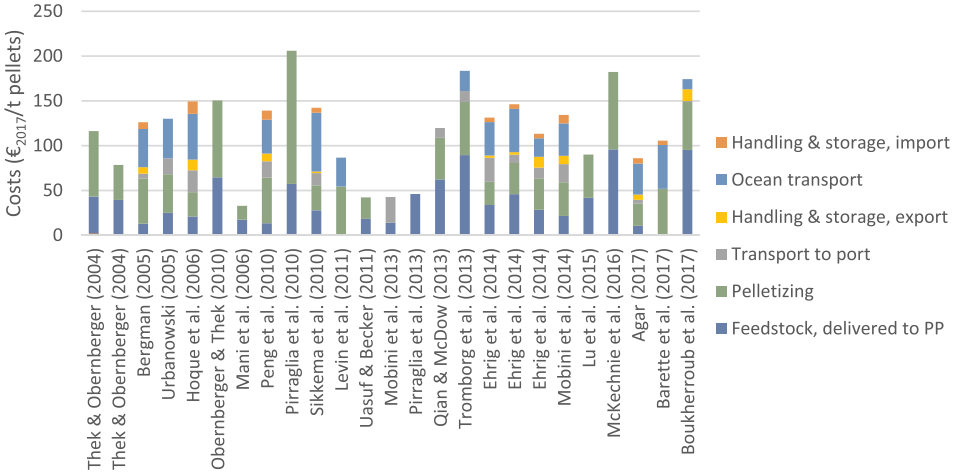

Fig. 6. Costs for selected wood pellet supply chain components as given in literature.

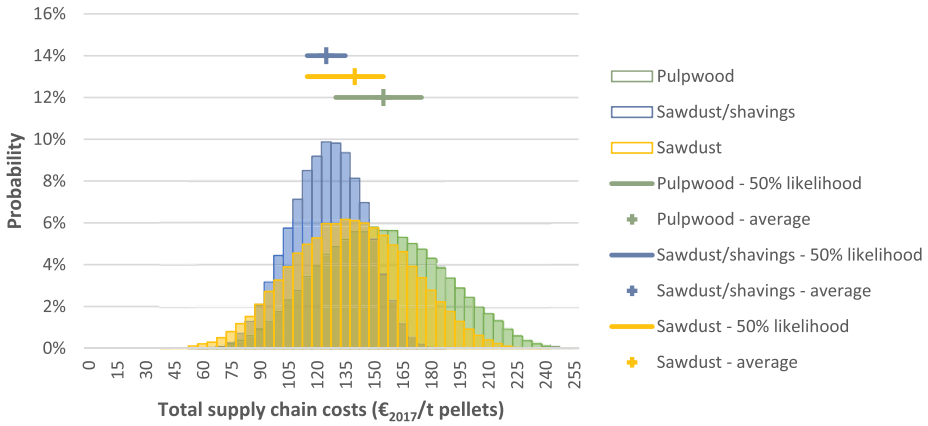

Fig. 8. Pellet supply chain costs likelihood of pellets produced from different types of feedstock, based on a Monte Carlo analysis of cost data from literature.

United States are somewhat higher than in Canada, at 43 compared to 37 €/t pellets. The Monte Carlo simulations of total pelletizing cost, including different pelletizing cost data, results in the lowest supply chain costs for Canadian pellets, at 155 €/t pellets, followed by the United States with total costs of 162 €/t. The 50%-likelihood values overlap for the largest part.

Shipping cost differ considerably in the literature, varying a factor 6.0 between 11 €/t and 66 €/t of delivered pellets. To understand the country impact, shipping costs were normalized for distance. The resulting variation remains however equally large, varying a factor 6.4, between 0.15 €ct./tkm and 0.93 €ct./tkm. This large uncertainty range can largely be attributed to one outlier. Without this one data point, normalized costs vary a factor 3.5, between 0.15 and 0.51 €ct./tkm.

3.2.3. Site selection

Calculated transport costs of feedstock to pellet plants vary between 0.7 €/t pellets, for a 12 kt/a pellet plant, and 23 €/t, for a 400 kt/a pellet plant. When correcting for different pellet plant sizes, the cost range remains large. When assuming 50 kt/a per year production for all pellet plant locations, transport costs range between 0.3 and 10 €/t pellets, with an average of 4 €/t. The lowest calculated transportation cost of pellets to ports are 3 €/t pellets, for a transportation distance of 42 km. The highest costs amount to 43 €/t, for pellets transported across 729 km. There is a clear link between distance and costs. This relation is not entirely linear because of differences in accessibility of rail infrastructure. The largest transportation distance among the set of pellet plants and ports is 839 km, for which the calculated transportation costs are 35 €/t pellets.

Table 4
Feedstock cost for different countries, in €2017/t pellets, as calculated based on a Monte Carlo analysis of cost data from literature.

	Average value			50% likelihood range
	Feedstock cost	Pelletizing cost	Total	Total
United States	43.0	49.7	155.0	138–185
Canada	37.4	48.5	161.7	129–181

3.2.4. Pellet plant size

Pelletizing costs for the small pellet plant, 50 kt per year, exceed the pelletizing costs for large pellet plants, including the additional costs of 2.7 €/t pellets required for pulpwood processing (see Table 5). For the assumed production size of 500 kt per year, additional average costs for feedstock transportation amount to 9 €/t pellets on average. From the different pellet plant locations, the pellet transport costs when assumed road transport only, for small pellet plants, is 7 €/t pellets more expensive. Using rail transport results in lowered costs for 23 out of 41 pellet mills. These rail transport costs do not include additional cost investments in rail infrastructure that might be needed at some locations. Rail infrastructure costs are difficult to estimate since these depend on factors such as the type of track, the specific contractor, local regulations and the total length of track required. An indication of total costs of new rail track is given in Ref. [58], amounting to about €2 million per kilometer of new track. Calculated shipping costs vary between 10 and 31 €/t pellets for Handysize ships between 2007 and 2018,

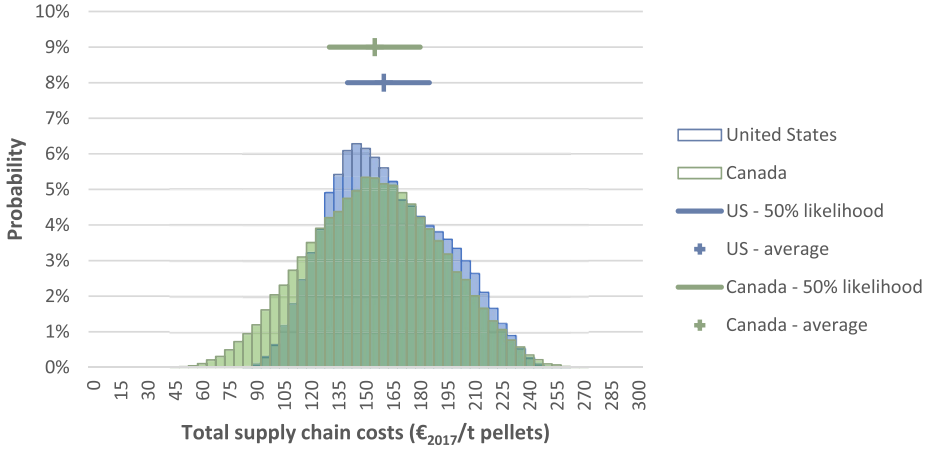

Fig. 9. Pellet supply chain costs likelihood of pellets produced in different countries, based on a Monte Carlo analysis of cost data from literature.

Table 5
Calculated cost components for small (50 kt/a) and large (500 kt/a) pellet plants, in €$_{2017}$/t pellets.

	Small	Small	Large	Large
	Range[a]	Average[a]	Range[a]	Average[a]
Feedstock		45.8		53.8
Feedstock transport	0.3–10.2	3.9	4.4–34.4	16.4
Pelletizing		53.0		41.5
Pellet transport	3.3–48.8	18.8	3.3–28.8	11.7
Shipping	11.8–33.5	20.9	7.1–20.3	12.7

[a] Cost of feedstock transport and pellet transport were calculated for specific pellet plant locations. The other cost factors were calculated without accounting for any supply chain differences other than size.

and between 7 and 26 €/t pellets for Supramax ships in the same period. On average, cost savings of using a larger ship are 4 €/t. Costs savings are largely, for 61%, the result of lower fuel consumption. The fluctuation of fuel costs is relatively small, varying a factor 3. The charter rates in the analyzed period fluctuated with a factor 11 for Handysize ships, and a factor 31 for Supramax ships (see Appendix A). The trade-offs between cost components for small and large pellet plants are discussed in more detail in section 4.2.

3.3. Comparison to market prices

Long-term price contracts are aimed at being mutually beneficial, providing both pellet plants and power plants with sufficient margin to sustain operations [59]. The prices of pellets traded on the spot market respond to supply and demand imbalances, generally resulting in higher prices in case of excess demand and lower prices in case of excess supply [59]. The large difference between contract prices and spot prices, peaking around the end of 2016, can be attributed to an oversupply of pellet production. The narrowing of the gap between contract prices and spot prices in 2017 indicates a balancing of supply and demand. After 2017, demand for pellets for both the electricity as well as the heat market have increased, further improving the position of pellet producers and narrowing the difference between spot and contract prices [59].

Supply chain costs as calculated were compared with contract and spot prices in recent years [59]. CIF ARA spot price varied between 107 €/t and 137 €/t pellets, as shown in Fig. 10. Total supply chain costs in the analyzed literature, calculated with averages for missing cost components, exceed these prices for respectively 24 and 18 out of 25 studies for the lower and higher points of this range. Most of the pellets exchanged between the United States and Europe are traded under long-term price contracts instead of spot prices. Comparing costs to the contract prices in Fig. 10, which varied between 131 and 182 €/t pellets, could therefore offer a more realistic insight. This resulted in literature results exceeding prices for respectively 18 and 8 studies. The total supply chain costs as calculated in this paper amount to 136–142 €/t pellets for assumed sizes of 50 and 500 kt/a. These costs are more in line with actual pellet prices.

Negative price differences between pellet costs in literature and reported prices could be the result of negative profit margins during the period of oversupply of pellets. In periods of low demand and low pellet prices, it could be beneficial for a pellet plant to temporarily reschedule or postpone debt payments to lower costs. A construction in which capital costs are temporarily lowered could eventually result in higher returns on debt or investment. The annualized capital investment on average contributes about 10% to the supply chain costs. By eliminating this cost component, the average marginal costs in literature reduce to 139 €/t pellets, ranging between 79 and 193 €/t pellets.

3.4. Total supply chain costs

Based on the work in this study, an overview of the most likely supply chain costs was created. These results were as much as possible calculated based on market data, supplemented with results from the literature review. Costs for feedstock were based on the US EIA data, resulting in a cost saving for the small plant using sawmill residues, see Fig. 11. Feedstock transport was also calculated to be cheaper for the small plant, adding up to increased costs of 21 €/t pellets for the large pellet plant for delivered feedstock. Pelletizing costs were calculated to be higher for the small pellet plant compared to the large pellet plant, resulting in lowered costs of 12 €/t pellets for the large pellet plant. Transport of pellets is more cost efficient for large pellet plants, based on the assumption that large pellets can utilize rail transport and larger ships, resulting in savings of 15 €/t pellets. Across the entire supply chain, the costs calculated for the small-scale pellet plant amount to 143 €/t pellets, which is 5% higher than the 136 €/t pellets for the large-scale pellet plant. These impacts are highly site specific, varying with feedstock availability and transport distance to end users. The results for the locations of existing pellets plants show an impact ranging between a cost saving of 38 €/t and a cost increase of 31 €/t for a large compared to a small plant. Whereas increasing the size of pellet plants could save pelletizing costs it would also result in increased feedstock supply areas and feedstock transport costs.

Certain cost components are quite sensitive to supply chain design assumptions. As can be seen in Fig. 12, the lowest and highest values for transport costs of feedstock and pellets for all pellet plant locations analyzed in this study create a large uncertainty. The costs for feedstock

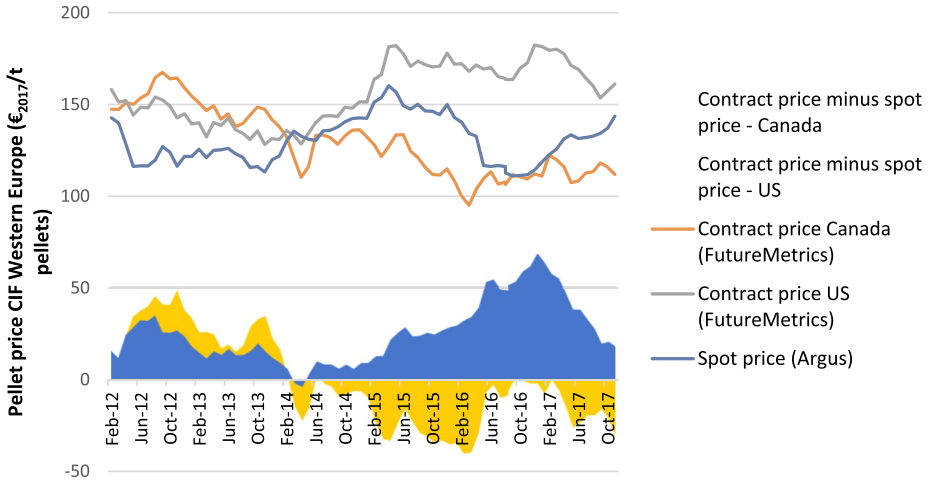

Fig. 10. Wood pellet contract prices, spot prices and the differences between contract and spot prices for Canada and the United States [59].

	Small	Large
Feedstock	46.4	55.6
Feedstock transport	3.9	13.1
Pelletizing	53.0	41.5
Pellet transport	18.8	11.7
Shipping	20.9	12.7

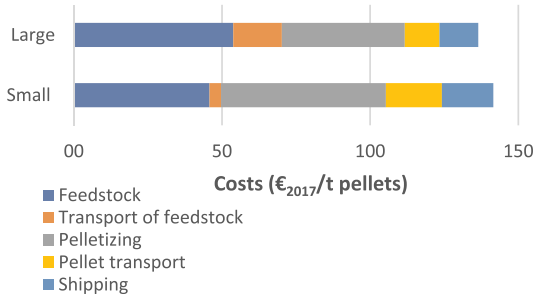

Fig. 11. Average calculated costs for small-scale and large-scale pellet plants at existing pellet plant locations in the United States, in €$_{2017}$/t pellets.

for individual pellet plants are highly dependent on local opportunities. Feedstock cost data used in this study is considered to be a reliable source of average costs. The assumptions on moisture content however introduce some uncertainty. Costs of pulpwood vary between 48 and 61 €/t pellets for assumed moisture contents between 45% and 55%. Costs of sawdust for pellet production range between 38 and 57 €/t pellets for moisture contents between 30% and 50%. Shipping costs are expected to vary over time with changing market conditions. For the data period assessed in this article, from 2006 to 2018, calculated shipping costs vary almost a factor 3.

4. Discussion

4.1. Uncertainty in literature studies

As shown in this article, the range of uncertainty in literature on wood pellet supply chain costs is significant, with total costs ranging between 88 €/t pellets and 279 €/t pellets. An implication of this factor 3.2 difference is that literature data is of limited use when predicting or calculating supply chain costs of actual supply chains. The uncertainty of individual costs components, notably the feedstock costs, pelletizing costs and shipping costs is larger still than the overall uncertainty.

Part of the cost variation can be understood by normalizing for differences between geographical scope or for differences in supply chain design. There is a significant difference in literature between the costs of distinct types of feedstock, affecting the total supply chain costs. Data on prices paid for feedstock in the SE US shows a smaller difference between prices of pulpwood and sawdust residues. Pellet production is a low margin business, with limited possibilities to compensate for higher expenses. Therefore, pellet plant business cases will have to be based on affordable feedstock. The type of feedstock used depends on local feedstock supply and opportunities as well as local competition. Differences between feedstock costs in different countries, according to literature, are much smaller and are of minor impact on the total supply chain costs.

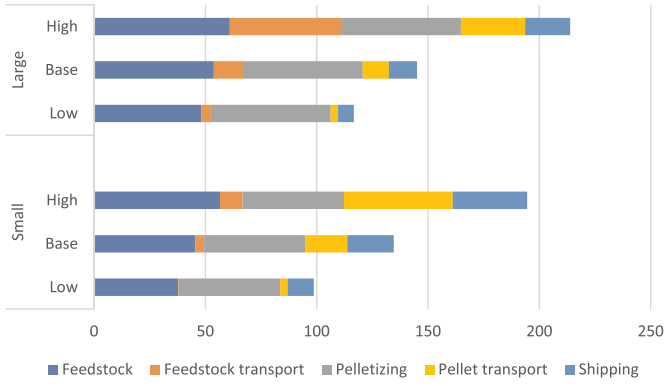

Fig. 12. Low and High costs for small-scale and large-scale pellet plants at existing pellet plant locations in the United States, in €$_{2017}$/t pellets.

The uncertainty in pelletizing costs is largest for operational expenses, varying a factor 8.4. This factor responds strongly to regional differences in aspects such as labor cost and electricity cost. The uncertainty in capital costs is smaller, varying a factor 4.8. This uncertainty is still large considering that the market for pellet equipment is well developed and equipment is traded globally. Within this category especially the cost of grinding equipment is uncertain, this could be related to the feedstock used in different case studies, and the significant differences in grinding requirements for different feedstocks. Uncertainty in shipping costs is large, ranging a factor 5.8 between lowest and highest costs. When accounting for transport distance, this uncertainty does not reduce. When also accounting for varying charter rates and fuel costs throughout time, the uncertainty does reduce slightly, however remains large at a factor 3.5.

As this study shows, variation of costs factors in literature is significant. A large part of the variation cannot be attributed to differences in scope, context or supply chain design. Data availability remains an issue. The confidential nature of commercial production of wood pellets also hinders the comparison of specific feedstock, production and transportation costs of various pellet plants.

4.2. Impact of supply chain optimization

The impact of different cost reduction strategies when reviewed as stand-alone measures seems very substantial. Lowered feedstock costs in Canada compared to other countries contributes to a cost saving of 6 €/t pellets. The use of sawmill residues could result in 10 €/t lower costs compared to the use of pulpwood. Cost savings because of site selection could amount to 10 €/t for the transport of feedstock to pellet plants and 40 €/t for the transport of pellets to export ports. Economies of scale result in 14 €/t lower pelletizing costs for a large pellet plant compared to a small pellet plant. Shipping costs of pellet transport in larger, Supramax, ships are 5 €/t lower than transport costs using smaller, Handysize ships. As explained in section 2.6.4. using Supramax ships is only cost effective for large pellet plants. The combined supply chain savings resulting from optimization strategies are significantly smaller because of various trade-offs in cost components. The impact of pellet plant size on total costs is relatively small, with total costs of 139 €/t for a small pellet plant and 137 €/t for a large pellet plant. This is the result of a combination of cost reductions and increases for separate components. A large pellet plant would benefit from cost savings of 7 €/t on pellet transport, excluding additional investments needed to connect to existing rail infrastructure, and 4 €/t on shipping compared to a small one. This is completely offset by the 13 €/t increased costs of feedstock transport. Economies of scale result in a pelletizing cost reduction of 12 €/t for a large pellet plant. On the other hand, larger plants are more likely to require the use of relatively expensive feedstock such as pulpwood, resulting in a feedstock cost increase of 8€/t. Trade-offs between various cost components show the complexity of supply chain cost optimizations. Appendix G shows the results of cost calculations for small and large pellet plants for the locations of existing pellet plants. The differences between the pellet plants are only the result of different

transport costs of feedstock and pellets, pelletizing and feedstock costs were kept constant for all pellet plants. These results show that the large variation in impact for individual pellet plants.

4.3. Feedstock market trends

In the SE US, forests are predominantly privately owned. The average land owner has a relatively small piece of land, with tree plantations sometimes considered an insurance or safety deposit instead of a source of continuous cashflow. Pellet mills will usually procure feedstock through short-term contracts, effectively continuously trading on the regional wood market. Market prices of feedstock depend on demand and supply, not only of pellets but also of the wood and paper market in general. Removals for pellet consumption make up a modest percentage of the wood market, 3% of total pine pulpwood removals in 2014 in the Atlantic and Gulf region, 15% of hardwood removals in the Atlantic region and negligible amounts of hardwood in the Gulf region [60]. Added demand for pellet consumption has had an assumed impact on the wood market and has contributed to regional increased pulpwood prices. Still, feedstock price changes in the US SE region are thought to be driven more by weather events, supply restrictions and the demand of non-pellet consumers [60]. The main driver of lumber prices in the SE US has historically been the US housing market, with new housing starts driving lumber requirements [61].

Regional or local timber feedstock costs are likely impacted by changing demand patterns. The availability of feedstock directly impacts the costs of feedstock, transport and processing, and should therefore be a very important criterium in site selection processes. The strong economic growth in the US in recent years is expected to result in increased domestic demand for timber, for instance for housing starts and wood products. At the same time, the pellet demand in Europe and other world regions is increasing [62]. This increased demand for wood resources from the United States could result in increased feedstock costs. Should pellet production increase significantly, supply chain conditions are likely to change. In the United States, pellet plants producing for the export market are currently located close to export ports. Increased pellet production is expected to result in more competition for feedstock and increased feedstock prices. Additional feedstock demand could shift pellet production to more inland regions, resulting in increased costs of pellet transport. Future research should focus on analysing the impact of increased pellet production on regional production shifts, and the effects this has on supply chain costs and sustainability implications.

Increased timber production could benefit pellet production. Pellets are often produced from lower cost feedstock such as sawdust, shavings or chips. Increased lumber production will result in higher availability of residues, which could result in lower prices for pellet feedstock. A growing pellet market creates other cost saving opportunities. Increased and more continuous production would enable the use of large bulk carriers such as Panamax sized vessels. If increased pellet production results in commoditization, this would allow for more cost-efficient bulk transport through hub-and-spoke based terminals.

5. Conclusion

Supply chains cost components in literature vary considerably, even for similar design assumptions such as the production country and type of feedstock used. Optimization strategies analyzed in this paper result in trade-offs between cost components and impacts vary strongly depending on the pellet plant location. Costs of feedstock transportation to pellet plants varies between 9 and 54 €/t pellets depending on the locations. Calculations based on actual prices paid for feedstock by US pellet plants, for roundwood/pulpwood and sawmill residuals, result in 8 €/t pellets higher costs for pulpwood. Using residues instead of pulpwood furthermore could save an additional 3 €/t pellets in reduced capital costs for grinding and drying equipment as well as an unquantified amount of operational expenditures. Averaged over all locations analyzed in the US SE, the calculated impact of economies of scale vary between a cost penalty of 46 €/t and a cost saving of 22 €/t pellets for larger pellets plant. Generalizing results based on similar supply chain design will likely introduce large errors. Cost optimization strategies must be tailored to specific pellet supply chains.

Analyzed supply chain costs generally exceed spot prices and contract prices as paid by pellet consumers in recent years. The increasing pellet production in the Southeast United States, however, indicates that the industry is generating enough revenue to remain a good business opportunity, suggesting an overestimation of costs in literature. This could be caused by the use of unrealistic input data from outdated sources of because of a misrepresentation of pellet market developments, such as the focus on small pellet plants. This study has incorporated recent market data for cost components where possible, resulting in a more realistic cost overview.

Acknowledgment

Funding: This work was supported by the Dutch Ministry of Economic Affairs, energy and innovation subsidy scheme SEI, Topsector Energy, executed by the Netherlands Enterprise Agency [grant number TEBE213008]

Appendix A. context variables

Shipping cost factors

Differences in shipping costs between the different studies could be the result of fluctuations in charter rates and fuel costs. Literature data was compared with calculated fuel and charter costs throughout time to analyze this component. A time lag of one year between data gathering and publication was assumed, hence, costs from literature studies were compared to shipping costs one year prior to the publication year.

Shipping costs calculated in this study, as shown in Fig. A.1 fall below the indicative freight prices as calculated by Argus Media. Costs between Savannah and the ARA ports for Handysize ships lie between about 12 and 20 €/t in the period 2014–2018 according to available data [63,64]. One of the reason behind the underestimation of shipping costs could be the exclusion of additional costs such as insurance, customs clearance or import taxes [55]. Data on these cost factors is not available in public literature. Total cost estimates in literature are generally given without explicit information on the cost components included.

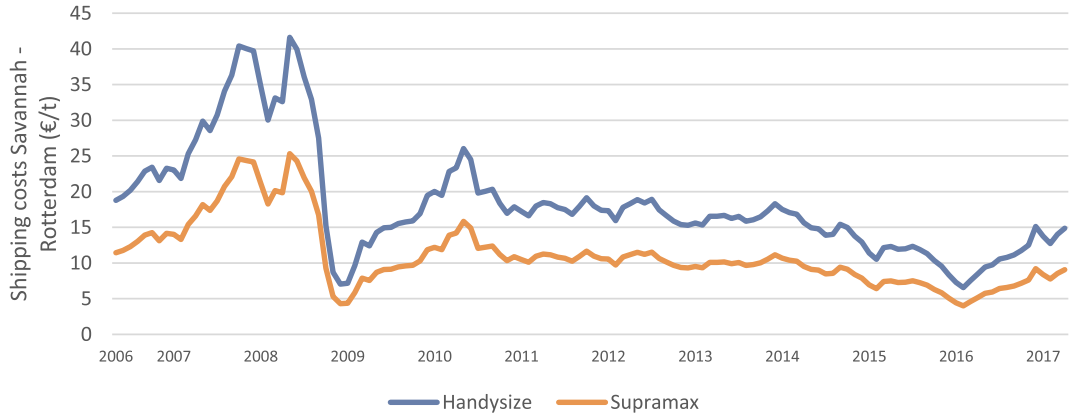

Fig. A.1. Calculated shipping costs in Handysize and Supramax ships, calculated between Savannah and Rotterdam based on time specific fuel costs and charter rates.

Exchange rate

The impact of varying exchange rates throughout the years was analyzed by calculating the average cost of the different components against average exchange rates in the years 2000–2017. These years were included to match the temporal scope of the studied literature. Next to the averages, also the minimum and maximum values of the components are analyzed. This analysis is repeated for only the set of literature studies that consist of values in dollar and Canadian dollar, to highlight the effect of exchange rates on cost estimates.

Shipping costs results

Calculated average shipping costs, based on historical charter rates and fuel costs, vary between 0.08 €ct/tkm in February 2016 and 0.48 €ct/tkm in May 2008 and. Yearly averages vary between 0.06 €ct/tkm and 0.36 €ct/tkm in 2016 and 2007 respectively. Comparing the normalized costs from literature with the calculated costs shows some correlation (Fig. A.2). In some cases, the literature values and calculated values overlap nicely. In several other occasions however, there is a significant difference between the literature values and calculated values. The distance-normalized shipping costs were again normalized for the historic difference, by factoring in the calculated costs in a given year compared to the average of all years (Fig. A.3). The resulting shipping costs vary a factor 4.2, when excluding the outlier however, the variation is reduced to a factor 1.8.

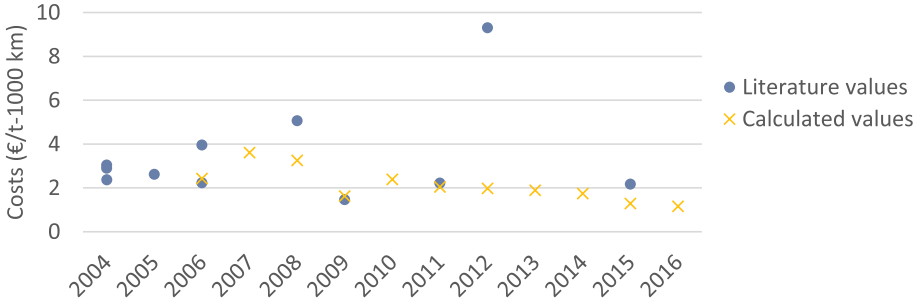

Fig. A.2. Normalized shipping costs and calculated shipping costs.

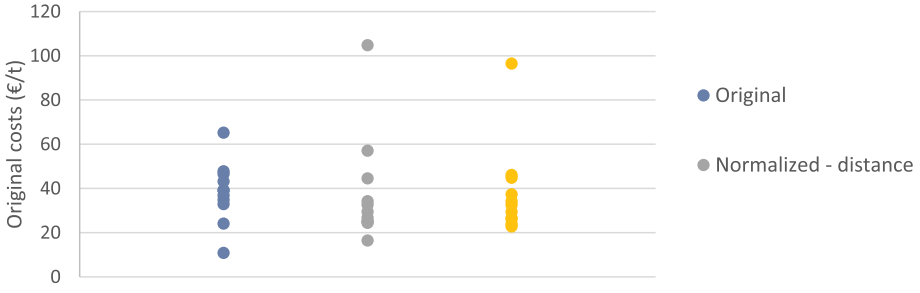

Fig. A.3. Normalized and original shipping costs.

Exchange rate results

Over the analyzed years, the average total costs range between 150 €/t pellets against the exchange rates of 2008 and 195 €/t against the exchange rate in 2001. The average over all years is 168 €/t pellets. The average of only those studies that use non-euro values ranges between 145 and 220 €/t pellets on average, in respectively 2008 and 2001. Looking at individual cost components, the absolute impact is especially large for the feedstock

component and pelletizing costs. For these components costs range between 34.6 and 55.7 €/t pellets and between 39.1 and 59.0 €/t respectively. Especially the impact of the dollar to euro exchange is significant, with the exchange rate varying between 0.9 $/€ in 2001 and 1.47 $/€ in 2008. The Canadian dollar to euro exchange rate ranged between 1.29C$/€ in 2012 and 1.62C$/€ in 2004.

Appendix B. transport costs calculations

Table B.1
Road/rail transport model costs factors.

	Value	Source
General		
Labor costs (€/h)	21	[65]
Diesel cost	0.68[4]	[66]
Road		
Loading/unloading time (h)	1	
Roundtrip factor[2]	2.5	
Capacity (tonne)	25	[67]
Variable costs (€/h)	18.4	[68]
Diesel consumption (l/km)	0.61	[68]
Rail		
Loading/unloading time (h)	1	
Rail car tariff (€/tonne)	12.93	[25]
Capacity (tonne)	3600	
Diesel consumption (l/km)	12.79	[67]

1. Only applied to loading and unloading time requirements, other costs are included in the rail car tariff.
2. Every hour of transport time is multiplied by a factor 2.5 to account for empty returns, breaks and delays.
3. Assuming rail car costs for a 65 car unit train of 90 MT grain cars (1588 $/car), applying exchange rate and inflation from 2012 [25].
4. Personal communication with US pellet plant representative, in line with Obernberger & Thek [5].
5. Data of 08-06-2018, assuming a dollar-euro exchange rate of 0.9.

Shipping costs methodology

Fuel consumption for the outward and return trip, $FC_{pellets}$ and FC_{empty} were calculated relative to the fuel consumed at full load, FC_{full}. This is based on the Admiralty formula, stating that, other factors such as speed being equal, the fuel consumption is approximately proportional to the cube root of the displacement [26]:

$$FC_{full} = Con^{*}(DWT - AT)$$

$$FC_{pellets} = FC_{full}{}^{*}\sqrt[3]{D_{pellets}/D_{full}} \quad \text{(B.1)}$$

$$FC_{empty} = FC_{full}{}^{*}\sqrt[3]{D_{empty}/D_{full}}{}^{*}ETF \quad \text{(B.2)}$$

The displacement of a ship at full load, D_{full}, is equal to the sum of deadweight tonnage, DWT, and lightweight tonnage, LWT:

$$D_{full} = DWT + LWT \quad \text{(B.3)}$$

The displacement of a ship filled with pellets equals the lightweight tonnage, additional tonnage such as fuel, water and crew, AT, and the weight of a full pellet load, FPL. Pellet loads are volume-limited, with the maximum load depending on the Stowage ratio, SR, and the density of the transported pellets, $\delta_{pelltes}$:

$$D_{pellets} = LWT + AT + FPL \quad \text{(B.4)}$$

$$FPL = DWT - AT/_{SR}{}^{*}\delta_{pellets} \quad \text{(B.5)}$$

The displacement of an empty ship is calculated form the lightweight tonnage, additional tonnage and ballast weight, BWT. Furthermore, an empty trip factor, ETF allocates a share of empty trips to the outward journey, depending on the capacity factor, CF, the share of distance travelled without load:

$$D_{empty} = LWT + AT + 0.8{}^{*}BWT \quad \text{(B.6)}$$

$$ETF = CF/_{1 - CF} \quad \text{(B.7)}$$

Total fuel costs were calculated for the different included ship classes. The total specific fuel consumption for each ship type was calculated by dividing the fuel consumed during the outward and return trip for the specific ship types over the load of pellets carried:

$$Total\ costs = \frac{FC_{pellets} + FC_{empty} * ETF}{Load} \quad \text{(B.8)}$$

Table B.2
Assumed characteristics of the three different ship classes included in calculations, Handysize, Handymax and Supramax.

Ship class	Handysize	Handymax	Supramax
Deadweight tonnage (t) [23]	28,000	40,000	57,000
Lightweight tonnage (t) [23]	8000	13,000	13,000
Additional tonnage (t) [23]	2000	3000	3000
Cargo capacity, weight (t) [23]	26,000	37,000	54,000
Volume limited load (t)	22,533	32,067	46,800
Stowage ratio (t/m^3) [23]	0.75	0.75	0.75
Capacity Factor [64]	0.3	0.3	0.3
CO_2 emissions, fully loaded (g HFO/tkm) [66]	4.9	3.9	3.0
Speed (knots)[a]	11.15	11.44	11.75
Fuel consumption, full (g HFO/tkm)	1.6	1.2	1.0
Density pellets, 10% MC (kg/m^3) [67]	650		
Emission factor HFO (t CO_2eq/t HFO) [66]	3.17		
Ballast [23]	25% of DWT		
Distance [67]	8710 km		
Loading/unloading capacity (t/day) [68] [b]	10,000		

[a] Average speed at sea was taken from the International Maritime Organization's third GHG study [69]. This data is provided for different ship types, with specifics on average deadweight. Interpolating between these data points yielded the assumed speed for the ship characteristics assumed in this study.

[b] An additional 50% of the total time was added to accommodate for periods of precipitation, when handling needs to be stopped to avoid adding moisture to the pellets.

Appendix C. Average cost of biomass for pellet plants

Table C.1
Feedstock prices as paid by U.S. pellet producers [70].

	Roundwood/pulpwood [76]		Sawmill residuals [76]		Exchange rate (euro/dollar) [61]
	quantity (short tons)	cost ($ per ton	quantity (short tons)	cost ($ per ton	
2017					
January	203	29.3	156	33.8	0.84
February	173	29.6	169	31.9	0.82
March	227	29.5	164	32.3	0.81
April	124	29.2	129	32.6	0.81
May	234	29.3	134	32.0	0.81
June	234	29.3	134	32.0	0.85
July	206	29.4	136	29.8	0.86
August	202	28.3	160	32.7	0.86
September	288	29.7	163	29.4	0.87
October	234	28.4	183	30.0	0.86
November	236	29.5	177	29.9	0.87
December	224	29.4	156	29.8	0.88
2018					
January	260	30.3	181	29.7	0.95
February	198	30.8	147	30.9	0.94
March	266	30.7	212	28.7	0.94
April	236	29.1	188	29.6	0.94
May	208	29.1	215	29.7	0.93
June	–	–	205	30.0	0.90
July	201	28.5	195	31.2	0.89
August	246	28.5	255	31.1	0.87
September	248	29.9	202	31.3	0.85
October	354	30.0	235	32.0	0.84
November	329	29.8	239	31.0	0.85
December	223	30.0	223	31.7	0.85

Appendix D. Moisture contents assumed in literature studies

Table D.1
Moisture content of different feedstocks assumed in the analyzed literature studies.

Source reference	Feedstock	MC	Feedstock	MC
1	Sawdust	55%		
2	Sawdust	57%	Wood chips	57%
3	Sawdust	53%	Shavings	19%
4	Sawdust	40%	Shavings	40%
5	Sawdust	40%		
6	Sawdust	55%		
7	Debarked pulpwood	55%		
8	Wood residues	40%		
9	Sawdust	53%	Shavings	19%
10	Sawmill residues	50%		
11	Sawdust	55%	Shavings	10%
12	Sawdust	29%	Shavings	11%
13	Debarked pulpwood	45%		
14	Pine pulpwood			
15	Chipped pulpwood	42%		
16	Pulpwood – Norway	45%	Shavings	10%
17	Sawdust/shavings - Canada	36%		
	Sawdust/woodchips - Australia	45%		
	Sawdust - Russia	55%		
18	Sawdust	29%	Shavings	11%
19	Pine pulpwood	35%		
23	–	48%		

Appendix E. List of pellet plants

American Wood Fibers Marion
Amite BioEnergy
Appling County Pellets LLC
Enova Wood Pellets Nahunta
Enviva Ahoskie Plant
Enviva Amory Plant
Enviva Pellets Cottondale LLC
Enviva Pellets Northampton LLC
Enviva Pellets Southampton LLC
Enviva Pellets Wiggins
Equustock Chester
Equustock Montebrook
Equustock Troy
Fiber Energy Products AR LLC
Fiber Resources Inc
Georgia Biomass
German Pellets Louisiana LLC
Hassell & Hughes Lumber Co
Hazlehurst Wood Pellets LLC
Henry County Hardwoods Inc
Highland Pellets LLC Pine Bluff
Lee Energy Solutions
Lignetics of Virginia Inc
LJR Forest Products
LowCountry Biomass
Morehouse BioEnergy
Nature's Earth Pellets NC LLC Laurinburg
Nature's Earth Pellets NC LLC Reform
New Biomass Energy LLC
NFR BioEnergy White Castle
O'Malley Wood Pellets
Potomac Supply LLC
Somerset Pellet Fuel
Southern Kentucky Pellet Mill Inc.
Telfair Forest Products LLC
Trae Fuels Ltd
Turman Hardwood Pellets
Varn Wood Pellets
Westervelt Renewable Energy LLC
Wood Fuel Developers LLC
Zilkha Biomass Selma

Appendix F. Reference numbers literature studies

Table F.1
Reference numbers used in the labelling of literature studies in figures and tables.

Reference number	Entry in reference list
1	[38] – Thek and Obernberger (2004)
2	[41] – Bergman (2005)
3	[36] – Urbanowski (2005)
4	[35] – Mani, Tabil and Sokhansanj (2006)
5	[56] – Hoque, Sokhansanj, Bi, mani, Jafari, Lim and Zaini (2006)
6	[5] – Obernberger and Thek (2010)
7	[33] – Pirraglia, Gonzalez and Saloni (2010)
8	[43] – Peng, Sokhansanj, Lim and Melin (2010)
9	[54] – Sikkema, Junginger, Pichler, Hayes and Faaij (2010)
10	[53] - Levin, Krigstin and Wetzel (2011)
11	[37] – Uasuf and Becker (2011)
12	[28] – Mobini, Sowlati and Sokhansanj (2013)
13	[45] – Pirraglia, Gonzalez, Saloni and Denig (2013)
14	[55] – Qian and McDow (2013)
15	[46] – Svanberg, Olofsson, Flodén and Nordin (2013)
16	[71] – Trømborg, Ranta, Solberg, Skjevrak and Tiffany (2013)
17	[1] – Ehrig, Behrendt, Wörgetter and Strasser (2014)
18	[42] – Mobini, Meyer, Trippe, Sowlati, Fröhling and Schultmann (2014)
19	[52] – Lu, Withers, Seifkar, Field, Barrett and Herzog (2015)
20	[44] – Mckechnie, Saville and Maclean (2016)
21	[47] – Barrette, Thiffault, Achim, Junginger, Pothier ad Grandpré (2017)
22	[6] – Boukherroub, LeBel and Lemieux (2017)
23	[39] – Agar (2017)

Appendix G. Supply chain costs of pellet plants at different locations

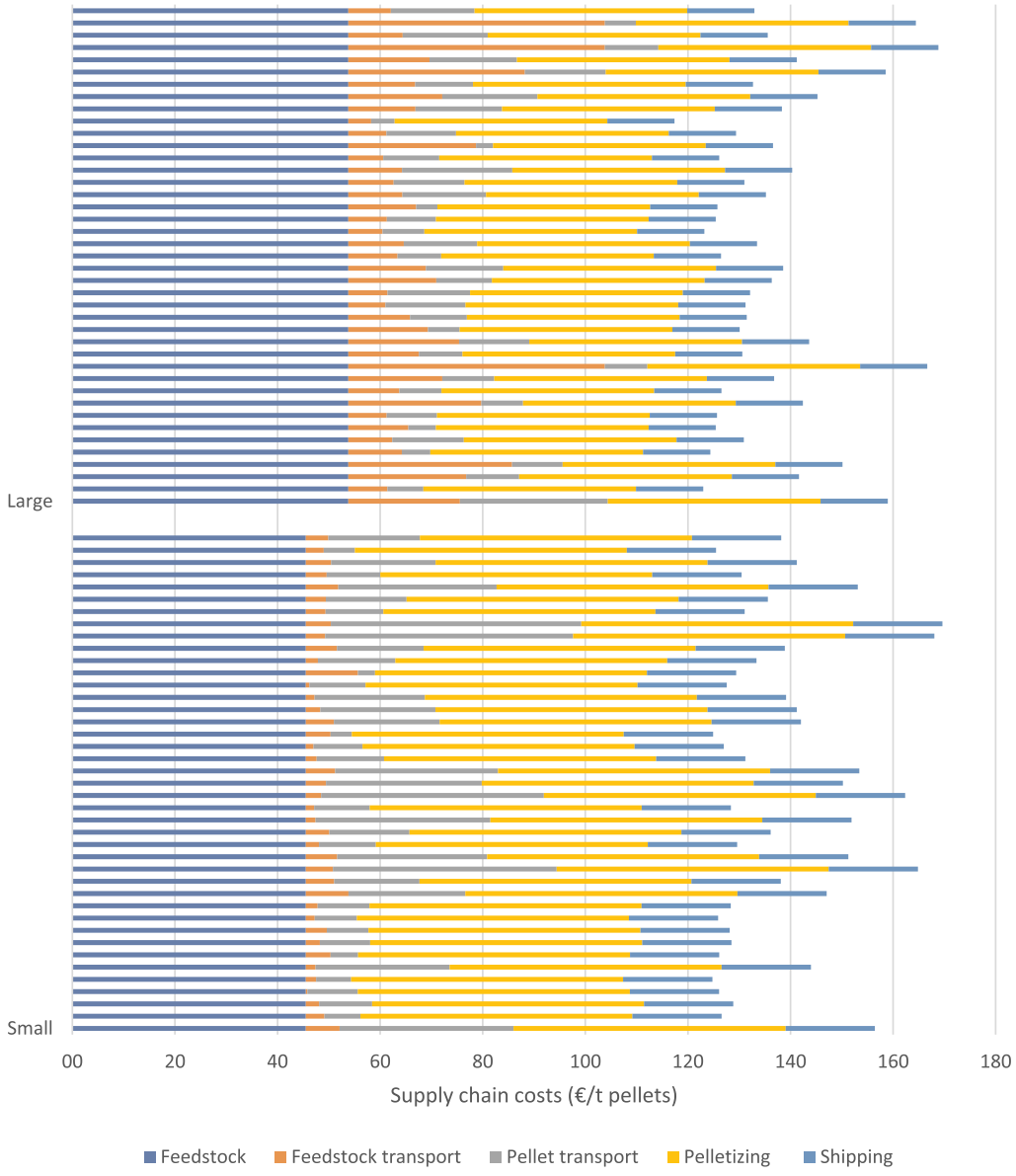

Fig. G.1. Supply chain costs of specific pellet plants at different locations within the Southeast United States.

Appendix H. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2019.109506.

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