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Opportunities and challenges for rail transport of solid wood biofuel

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The use of solid biofuel for energy in heating plants has increased drastically during the last decades. This substantial and increasing demand has placed focus on delivering biofuel to the plants, as logistics issues are considered one of the key challenges for further increased use of biofuel. Problems in sourcing enough fuel locally due to the increasing size of power plants and environmental concerns has sparked an interest in using multimodal road-rail transport as a cost effective and environmentally friendly way of long-haul transport. A case study is performed at a Swedish district heating plant to investigate the potential of introducing multimodal transport. Extensive calculations are performed in the design and operation of a multimodal system, showing both costs and CO2 emissions. This is analysed in relation to key logistical challenges in the industry. A best case scenario is identified. Conclusions are that the potential for multimodal transport is greatest among the largest plants with large volumes to achieve high resource utilisation of the transport equipment. A shift from road to multimodal transport is facilitated by that a large share of the current road transport flows already pass through a terminal, which improves multimodal transport competitiveness against road transport as this reduced the cost difference. This study leads to better understanding of the strengths and weaknesses of multimodal biofuel transport and has practical implications for anyone in the process of designing such systems.

Keywords: *wood biofuel, heating plant, intermodal, rail, wood chips, transport.*

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1. Introduction

The use of solid biofuel for energy in heating plants for district heating (DH) increased drastically during the decades after the 1970's oil crisis (Björheden, 2006), largely as a means of creating a more sustainable energy system. This development was particularly prominent in Sweden (Ericsson, et al., 2004, Björheden, 2006), which today largely utilises forest fuels in district heating plants (HP). From practically nothing in 1970, wood biofuel now accounts for about 24 TWh, or 37%, of the total energy for DH in Sweden (Swedish Energy Agency, 2014, Swedish Forest Agency, 2014), making Sweden the European leader in the use of biomass for DH (Connolly, et al., 2013). Today, there are close to 500 heating plants (HP) in Sweden, and of the Swedish municipalities all but a handful apply district heating (Andersson, 2012).

The use of DH is most widespread in Sweden and the other Scandinavian countries, accounting for about 40-60% of the residential heating market, compared to 13% in the rest of Europe (Connolly, et al., 2013) and 3% in the US (Euroheat & Power, 2014). In EU-27, about 15% of DH energy comes from renewable sources (mainly biofuel) (JRC, 2012) and the EU has required its member states to promote the use of biofuel for DH (European Commission, 2013). Global

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interest is also substantial as 63% of the DH actors in the world's 30 largest DH countries have investment plans for renewable energy sources (Euroheat & Power, 2014).

This substantial and increasing demand has placed focus on supplying the HP with fuel, as logistics issues are considered one of the key challenges for further increased use of biofuel (Rentizelas, et al., 2009, Gold and Seuring, 2011, Svanberg and Halldórsson, 2013). Keeping logistics costs low is important for a competitive biofuel system, which is of key importance in reducing both dependence on fossil fuels and the greenhouse effect. Savings in greenhouse gases amount to approximately 90% when fossil fuel is replaced with biofuel. Biofuel also brings a very positive energy balance, as the energy consumed to produce biofuel only represents 2-5% of the energy in the biofuel, compared to 15% for fossil fuel (Lindholm, 2010). Transport has a significant impact as it accounts for 37% of the energy consumed in the biofuel chain (Lindholm, et al., 2010) or 25% of the total cost (Brunberg, 2014).

Currently, 84% of the energy from Swedish HPs is generated from wood biofuels transported by road only. Road is the traffic mode the industry perceives as best meeting their current logistics requirements in regards to accessibility, reliability, transport time, and frequency (Awais and Flodén, 2014). However, the increasing HP sizes make it difficult to source enough fuel locally, thereby forcing the HPs to source further away. As an example, a large HP in Sweden can require up to 17 000 tonnes of fuel per week (400-500 truckloads). Some regions, such as the region around Stockholm, Sweden, already have a significant shortage of biofuel (Roos, et al., 2000, Björheden, et al., 2010). As HPs are forced to source further away, road transport becomes a less attractive option from both cost and sustainability perspectives. Biofuel is a low value commodity that has difficulties carrying any large transport costs. This has sparked an interest in other traffic modes, such as rail and sea, as these generally have lower costs and better environmental performance for long haul transport (Mahmudi and Flynn, 2006, Enström and Winberg, 2009, Björheden, et al., 2010, Frosch and Thorén, 2010, Tahvanainen and Anttila, 2011, Danielsson and Liss, 2012, Routa, et al., 2013, Svanberg, et al., 2013). Further, larger HPs bring the possibility of positive scale effects in plant operations, but the size of the plant is constrained by available fuel in the region and high transport costs (Mitchell, et al., 1995, Kumar, et al., 2003, Cameron, et al., 2007). Also, efficient long distance transport brings a possibility to utilise price differences in raw material between different geographical areas, although currently the domestic price differences in Sweden are fairly low (Swedish Energy Agency, 2015). However, despite the potential benefits and increasing attractiveness, rail based transport solutions for biofuel only amass a market share of a few percentage points (Flodén, 2015).

A few very large Swedish HPs have already implemented multimodal solutions where the focus has been on road/rail combinations. Typically, the more flexible road transport is used to transfer and consolidate the biofuel to a terminal, from which low cost rail transport is used. Rail has lower variable transport cost per transported km and lower environmental impact than road transport, but instead have higher fixed costs and require large freight volumes, terminals, and special infrastructure. The fuel is transported by rail either directly to the HP or to a terminal from which it is transported the last leg by road. Intermodal transport has received much political interest in recent years (European Commission, 2006) and has been found in a European setting to have less environmental impact than competing modes (INFRAS/IWW, 2004, Lindholm and Berg, 2005, Kreutzberger, et al., 2006). In an overall review intermodal transport has been identified as the most sustainable transport option in a Swedish setting concerning all three pillars of sustainability (economic, societal, and environmental) (Flodén, 2015). However, all traffic modes have different characteristics and it is important to examine each traffic mode and terminal handling in the context of biofuel transport to understand the potential of each mode and how they can best be combined.

Previous studies considering rail and/or multimodal transport of biofuel include Mahmudi and Flynn (2006), who studied the competition between road and rail in a Canadian setting for wood chip and straw, estimating a break-even point between road and multimodal transport of 145 km for wood. The study uses North American costs based on estimates from a rail operator, but does not study possible design options or improvements of the rail system. Emissions are not included. A study on US conditions was made by Gonzales, et al. (2013), investigating rail transport of wood chips along with other commodities and transport modes using regression analysis. Rail costs were based on public tariffs, and factors explaining the tariffs, such as distance and volume, were identified. Eriksson (2008) focuses on the energy use in a life cycle perspective by studying one local, one domestic, and one international chain from Sweden. Different transport options (combinations of truck, train, and ship) and formats of biofuel are studied (chips, pellets, and bundles) in a total of 40 options, of which 19 are national. Distances are fixed. For the national option (approx. 600 km), combinations including train and/or ship are considered to result in the lowest cost and CO_2 emissions. Eriksson's rail cost are based on Hamelinck, et al. (2005), who in turn base their cost on Börjesson and Gustavsson (1996), who base their costs on a number of local Swedish reports from the early 1990s. Hamelinck, et al. (2005) studies international long-distance, mainly intercontinental, transport of various biofuels. For a transport from Scandinavia to the Netherlands (1100 km), Hamelinck *et al.* concludes that a supply (including cost of biomass) of pellets or logs by ship is the most cost effective option. Transport of chipped wood residues by rail has the highest costs. The high production cost of the biomass used for chips is the most influencing factor. Börjesson and Gustavsson (1996) study an early stage of biofuel development in Sweden. The study focuses on emissions (CO2, NO_x, CO, HC), energy use, and available biomass in order to identify the future potential use of biomass in 2015. Rail transport is included as one potential mode of transport but not studied in detail. Tahvanainen and Anttila (2011) study the biofuel transport in a Finnish context through a GIS model where 10 supply chains with different transport modes and types of biofuel are studied. Chipped wood has the lowest transport costs and train transport is not competitive until transport distances longer than 160 km. Costs are based on average costs in the Finnish forest industry. Kanzian, et al. (2013) builds an optimisation model of the biofuel transport system in five Austrian provinces to optimise profit and minimise CO_2 emission. Rail cost was based on the official price list for freight wagons. Svanberg, et al. (2013) studies the special case of the new types of torrified biofuels and calculates the production and supply chain cost, including rail, with a focus on determining the optimal size of a torrification plant. A review of modelling a wide range of biomass-to-energy supply chain operations can be found in Mafakheri and Nasiri (2014).

However, previous studies have not gone into detail on the transport system. In particular, the design and cost of the rail system have not been studied in detail. Most papers only present rail costs as a given cost per transported volume without explaining the underlying assumptions. It can further be seen that the articles define and calculate cost differently, have a different scope of the calculations, and include different aspects that make the results hard to compare, in particular since not all assumptions are stated. It is therefore hard to compare, e.g., "rail cost per kwh" between different studies as it is not clear what activities are included in the costs. This was also concluded by Wolfsmayr and Rauch (2014) who, after reviewing more than 100 scientific papers on biofuel supply chain, identifies a need for future work for clarification. Among the previous studies, Routa, et al. (2013) in particular highlight the need for more studies into intermodal transport, and Tahvanainen and Anttila (2011) underline the need for better cost estimates for rail transport. Designing a rail system is a complex task with many influencing factors. It is therefore not enough to just look at the rail system as a "black box" with a given cost, but rather to investigate in detail how the system could be designed to help improve the potential for biofuel transport by rail. A detailed and transparent analysis would help decision makers in identifying which factors are most important in building a successful system.

This paper aims to contribute to this through a transparent study of multimodal transport of solid biofuel for heating plants, focusing on the design of the rail transport system. The study will calculate costs and CO_2 emissions for the multimodal transport system and identify the influence of key design factors. Particular care has been given in explaining assumptions and presenting the input data used. A further aim is to investigate how the key design factors affect the logistical challenges in relation to the multimodal transport of biofuel. This study leads to a better understanding of the strengths and weaknesses of multimodal biofuel transport and have practical implications of anyone in the process of designing such systems. The study is set under Swedish conditions as the use of biofuel for HPs are particularly well established in Sweden (Ericsson, et al., 2004, Björheden, 2006). To reach transparency in the paper, case studies are the selected method as they enable specific conditions to be studied in detail. Case studies are suitable when aiming to understand how the studied object behaves in a contemporary setting (Yin, 1994). Supplying a medium sized HP in Gothenburg, Sweden, will be used as a case. The case study is further explained in section 3.

The paper starts with an introduction to logistical challenges in the biofuel industry (section 2), followed by a case description (section 3). The case results are presented in section 4, followed by analysis of the case in (section 5) and conclusions (section 6).

2. Logistical challenges in the supply chain

This section discusses the main logistical challenges in the transport chain and explains where they impact a typical supply chain. Awais and Flodén (2014) identify five key logistical challenges in solid wood biofuel transport chains: seasonal variability, storage, chipping, low density, and dependency on political policies. In wood biofuel chains the demand and stocks vary a great degree depending on the *seasonal variability* in the industry, as both the demand and forest management are seasonal. This results in the underutilisation of expensive machinery and equipment, causing an increase in annual operational costs. Due to the climate, the need for energy is greatest during cold winters and very low during warm summers. Most Swedish biofuel HPs close during the summer and only operate between approximately late August and April. The daily demand also varies significantly due to the outside temperature. *Storage* is therefore needed for a smooth flow of raw materials, which involves logistical decisions regarding the location, size, and equipment present at a storage facility. *Chipping,* or the process of transforming the wood into smaller pieces to burn, is also an essential part of the supply chain. This increases the density of most biofuel, allowing for more efficient transport but also affects the storage space necessary for the fuel. Chipping is normally performed at the roadside in the forest, but can also be performed at the storage terminal or at the HP. Different machines are commonly used at the different locations, thus resulting in different costs and energy consumption (Hamelinck, et al., 2005). Chipping at a terminal/HP is more efficient but requires a low density transport from the forest. In general, wood biofuel, both chipped and unchipped, is a *low density* and low value good that requires good capacity management in the vehicles and at the storage terminals. This low density makes transport an important cost factor in the supply chains (Gold and Seuring, 2011). Political interest in biofuel is great as a means to reach a more sustainable society and to reduce CO_2 emissions and climate change, which makes the supply chain sensitive to *political policies*. This is not only related to the biofuel industry as such, e.g., energy taxes on renewable energy, subsidies, permits, emission trading etc., but also to regulations on the transport, e.g., allowed vehicle sizes, infrastructure fees, fuel taxes, etc. Most district heating plants are also municipality owned (Svensk Fjärrvärme, 2014) and are thereby subject to political decisions by their owners, such as environmental requirements in tendering.

2.1 *A typical supply chain*

A typical supply chain can be divided into five steps: 1 Pre-haulage, 2 Terminal, 3 Long-haul transport, 4 Post-haulage/delivery, and 5 System. A more detailed description of a typical supply chain can be found in Routa et al. (2013) or Wolfsmayr and Rauch (2014).

2.2 *Pre-haulage*

The supply chain starts in the forest where the wood biofuel are harvested at several dispersed locations. The biofuel used are normally forest residues (branches, etc.) and other types of by-products from tree harvesting and the forest industry with limited or no other uses. The biofuel is then transported by road, either directly to a power plant (49% of energy) or to a terminal/*storage* (Awais and Flodén, 2014). The amount of fuel passing a terminal ranges from 20% to 60% for individual companies (Enström, et al., 2013). Road transportation is mainly used for the initial and final haul of the wood biofuel (Björheden, et al., 2010). See Figure 1. HPs try to keep the road transport distance as short as possible due to the low value and density of the fuels. Another origin of the supply chain is the wood processing industry (e.g., sawmills), where by-products such as sawdust are collected. The raw material is here concentrated in one location and some wood processing industry sites also have rail access that enables direct pick-up by rail at the site.

For road transport, the biofuel is normally transported by wood chip container trucks with detachable biofuel containers carrying 40 m^3 of fuel each, with three containers per truck. The wood chip container trucks are equipped with hook lifts, where the truck pulls the containers up from the ground with a hook, thus not requiring external handling equipment to load, unload, or empty the containers. Also, wood chip trucks with a tilting superstructure can be used, carrying 120-130 m^3. These trucks are more efficient for long haul transport, but have difficulties accessing loading sites in the forest and are therefore mostly used from terminals. Rotary containers carrying 45m^3 are often used for the rail transport, where a fork-lift truck turns the container upside-down with a rotator and empties the fuel.

2.3 *Terminal*

Chipping is carried out either at the forests or terminals to increase the *density* of the biomass and improve transport efficiency (Björheden, et al., 2010, Eliasson and Picchi, 2010, Spinelli, et al., 2011). Chipping in the forest is most common. Biofuel is *stored* at the terminals, with more short term storage for a few days at the plants. However, storage also takes place in the forest where the biomass is left unprocessed in piles by the harvesting site in the forest for 6-12 months to dry before being picked up (c.f. Lehtikangas (1999).

2.4 *Long haul transport*

Rail or ship transport can be used for long distance transport from the terminal to the plant/other terminal (see Figure 2), although 84% of the energy used in Swedish HPs are transported by road only (see Figure 1) (Awais and Flodén, 2014). Rail transport cannot be used directly from the forest due to the lack of infrastructure and the small amount of wood at each harvesting site. The *seasonal variability* has a particularly large impact here as rail is a less flexible mode of transport with much dedicated equipment. Due to inflexibility in planning, contracts, application procedure for time tables, etc., the rail system is fixed for the entire season; i.e., the number of wagons and the schedule do not change. Therefore, rail is normally used for the base flow that is stable throughout the season while road is used for the peaks.

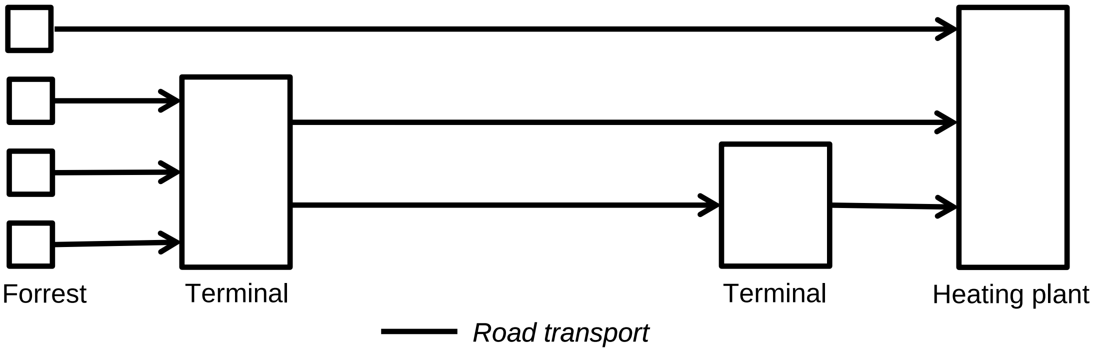

Figure 1. The all-road transport system

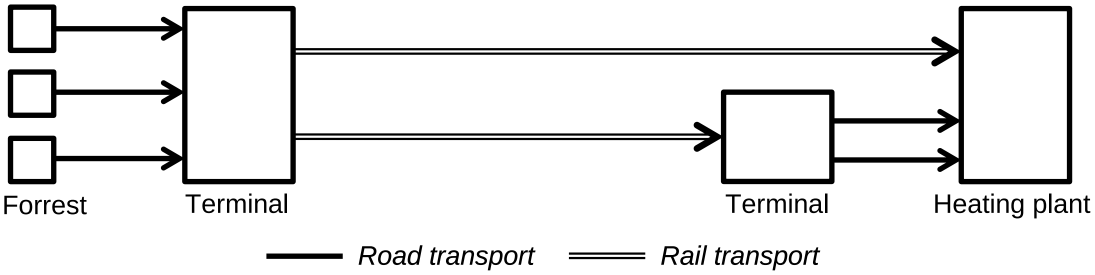

Figure 2. The multimodal transport system

2.5 *Post-haulage/delivery*

Larger heating plants sometimes have rail access where the train unloads directly at the plant, but often an intermediate terminal is used and the final transport to the plant is made by road. See Figure 2.

2.6 *System*

The system refers to how the overall market for biofuel works and are influenced by outside actors such as *political decisions* and conditions such as *seasonal variability*. Typically, biofuel is sold by a biofuel company and includes delivery to the HP. Since the demand for heat is dependent on the daily temperature, contracts are often signed per season with call-offs made each week for next week's demand. Transport flows are unbalanced with little demand for transport from the populated areas with HPs to the forest areas, often resulting in empty returns for the transport equipment. For a further description of the biofuel market and overall system, see e.g., Ericsson, et al. (2004), Olsson and Hillring (2013), Flodén and Williamsson (2016). For the Swedish DH sector see Magnusson (2012), and for historical development see Andersson (2012) and Björheden (2006).

3. Case

The method chosen for the study was a case study of a medium size HP in Gothenburg, Sweden. The plant is located next to a rail line and has expressed interest in investigating the potential use of rail transport and kindly agreed to cooperate with this study. Due to its medium size, the plant is an interesting study object as it is large enough to be a potential candidate for rail transport but not large enough to make rail an obvious choice. The plant is located in a residential area close to the city centre. At full operation, the plant consumes approximately 17 GWh per week and is currently fuelled by wood residue chips, log chips, and stump chips. The plant is used for the base load in the district heating grid and is operated from early autumn to late spring. The plant has road access and access to the rail network via a non-electrified rail siding, and is located next to an electrified major shunting yard and rail line. Local environmental regulations stipulate that chipping is not allowed at the terminal. Deliveries are allowed 24/7 but the plant tries to avoid weekend and night deliveries so as not to disturb the neighbours. The storage area is limited to 10 000 m^3, or roughly a 60 hour supply (Friday evening to Monday morning). All fuel is sourced locally. The plant is currently supplied by all-road only with about 40 trucks delivering to the plant each day. All fuel is chipped road-side in the forest and the supplier is responsible for the transport.

3.1 *Case methodology*

A potential rail system for the plant is designed and subjected to a sensitivity analysis where key variables are changed to determine the key factors for successful multimodal transport. The prospective rail system is designed by calculating the break-even distance between road and rail transport. Within this region a search is made for potential terminals and sourcing locations, and a rail system is designed in detail. The rail system is then subject to a number of scenarios, each focusing on key characteristics of the system. Based on these scenarios, a "best case" scenario is designed combining key characteristics from previous cases.

Based on the underlying cost calculations (see Appendix A) the variables with the largest potential impact on the system have been selected and divided according to the five steps of the supply chain. See Table 1. Although realistic values of the variables have been used, not all variables are under the direct control of the HP or system operators (e.g., length of season depends on the outside temperature). The intention here is to show the effect if these variables could be influenced (e.g., transport season could be extended by adding storage) and not imply they are necessarily easy to implement. If a scenario shows a very good effect on the rail system, then this should be seen as an indication that a potential implementation should be investigated further. A limitation of the study is that costs in reality are situation dependent. Different operators will have different equipment, operational procedures, accounting models, cost structures, etc., resulting in somewhat different costs. This study therefore focuses on the difference between the scenarios to show the impact of the key variables. If nothing else is stated for each scenario, the assumptions and variables are the same as in the base scenario.

Table 1. Key variables

Stage	Key variables
Stage 1 Pre-haulage	Distance to terminal
Stage 2 Terminal	Terminal costs
	Shunting efficiency
	Chipping location
Stage 3 Long-haul (Rail)	Type of rail engine
	Train length
	Utilisation of rail engine and wagons
	Fill rate on train
	Type of load unit
Stage 4 Post-haulage/delivery	Via receiving terminal
	Distance from terminal
	Intermodal container transport
Stage 5 System	Type of biofuel
	Return flows
	Round trips per week
	Length of season

A modelling tool was developed in Microsoft Excel based on Flodén (2011). Based on the system design and cost input data, the model calculates costs and emission data for the system. Input data is divided into fixed and variable costs, where the fixed costs are allocated based on the utilisation in the current system. See Appendix A for input data, sources, and structure of calculations. Much care was taken in finding good input data for the model, in particular the cost data. Six telephone interviews and one e-mail interview with road (1), rail (1), and sea (e-mail) biofuel transport companies and a terminal company (1), forest company (1), and energy companies (2) were performed to further understand the operations. The interviews lasted about 60 min each and were recorded. Site visits have been made to four biofuel plants and two terminals. Data was collected from literature and directly from supply chain actors in Sweden. Real cost data were gratefully received from four industry actors in different parts of the supply chain. Some reported data for only parts of the operations. As can be expected, the cost estimates varied between the different sources. The cost data was refined by combining the data from the industry and the literature, and checking the results against our own calculations of expected costs. This resulted in a data set for the cases containing a reasonable appreciation of the costs. Thus, the data used in the scenario does not represent the costs of any specific actor, but can be viewed as an average cost level in the Swedish industry. All selected data were independently validated with at least two industry representatives, while some data were validated with as many as five representatives. The selected cost levels were also validated with a reference group of biofuel industry actors from road, rail, power plant, and forest sectors. Costs were estimated in SEK, Swedish kronor, kr (2013: approx. 9 kr = 1€). Cost levels represent the year 2013. Older data where adjusted according to index.

3.2 *Break-even distance*

As a first step in designing the base scenario, the break-even distance between road and rail transport is of key importance to determine the minimum length of rail transport. Based on discussions with industry representatives, a typical biofuel setup is selected, consisting of a train with 22 wagons (type Sgns), an electric engine (type Rd), and 45m^3 load units with rotary unloading, transporting 2 300 MWh of logging residue chips. Rail has a 50 km pre-haulage by road to the rail terminal, using a 93 MWh woodchip container truck. The train runs directly to the HP and is unloaded at the plant. Diesel shunting is used at both the terminal and the plant. The train is assumed to run three or five days per week, 26 weeks per year. The full round trip, including cost of the empty return transport, is included. Road transport is represented by a wood chip truck carrying 103 MWh, where 40% of the flow is transhipped at a road-road terminal as a current typical setup (Enström, et al., 2013). Twenty-three trucks are needed for the road transport and are assumed to return empty. Chipping is assumed to take place roadside in the forest in both systems. The calculations show the break-even distance at 250 km for three days. See Figure 3. Extending the train operations to five days per week pushes the break-even distance down to 180 km, showing the positive effect of high train utilisation. If pre-haulage is excluded, the break-even point is pushed to around 190 km for a three day system and 120 km for a five day system. Further, the energy content and density can vary between different batches of biofuel, depending on the region, time of year, moisture content, etc. A change in density and energy content might influence the break-even point between road and rail, as road transport by wood chip truck is constrained by weight, i.e., the maximum allowed loading weight is reached before the volume is filled. Rail transport, in contrast, is constrained by volume where the volume of the rail wagons is filled before the maximum weight is reached. Rail therefore becomes more competitive against road the heavier the biofuel becomes. A rotary container on an Lgns wagon has approximately 1.4 tonnes available loading weight when the volume is full, assuming the densities used in this scenario. This is the equivalent of approximately 90 MWh extra capacity on the train or a 4% increase in energy transported at basically the same cost. Similarly, road gains in competitiveness for lighter fuels as the wood chip truck has approximately 8 m^3 (6 MWh, 6%) available capacity when the maximum weight is reached.

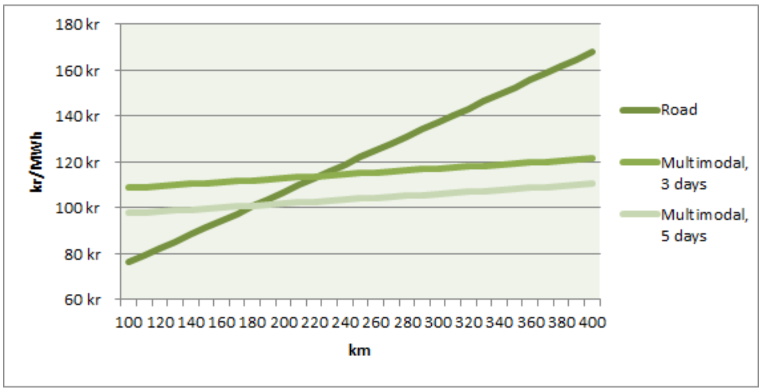

Figure 3. Costs for the biofuel system.

From an environmental perspective, the advantage of the multimodal solution is clear. See Figure 4. The multimodal solution produces significantly lower CO_2 emissions compared to the all-road solution. The main difference is in the pre-haulage by road and chipping, as the rail transport has very low CO_2 emissions due to the very clean Swedish electricity mix largely based on hydropower and nuclear energy. The average Swedish emissions are used, although it should be noted that the Swedish Transport Administration actually purchases even cleaner electricity certified as "Good Environmental Choice" according to the Swedish Society for Nature Conservation's criteria, thus produced from only hydro power with almost no CO_2 emissions (Trafikverket, 2013). However, in a European comparison, the average Swedish emissions are still very low and only about 5% of the OECD Europe average (Brander, et al., 2011).

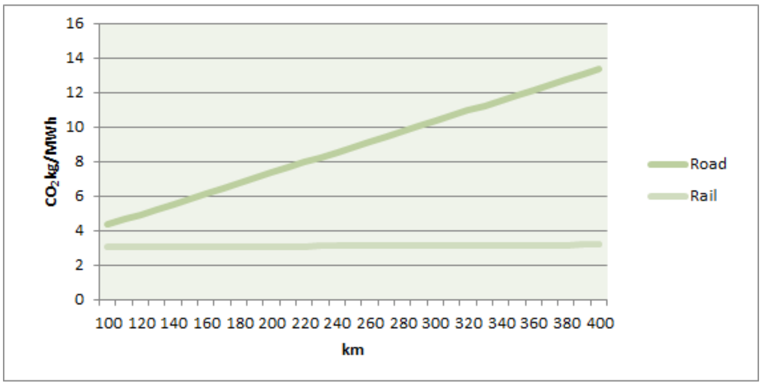

Figure 4. Emissions for the biofuel system.

3.3 *Base scenario*

The base scenario design is based on interviews with the Gothenburg heating plant and terminals in the area and was validated with the plant. Main characteristics can be found in Table 2 and the map in Figure 5. Among the major sourcing areas for biofuel in Sweden, the two closest areas above the break-even point are the regions of Småland and Dalarna. Due to the importance of a high utilisation of the train, a five day per week scenario is selected, operating three days a week to Småland (265 km) and two days a week to Dalarna (471 km). In Småland, logging residue wood chips are picked up, which is the most common biofuel in Sweden. In Dalarna bark is picked up. Dalarna is rich in wood industries, whose by-products are the second most common fuel (Awais and Flodén, 2014). The train schedules are validated with a train operator. In total, the system delivers 9.8 GWh weekly, corresponding to 58% of HP demand when operating at full capacity. Rail covers the base demand of the plant while the fluctuations are managed by more flexible road transport.

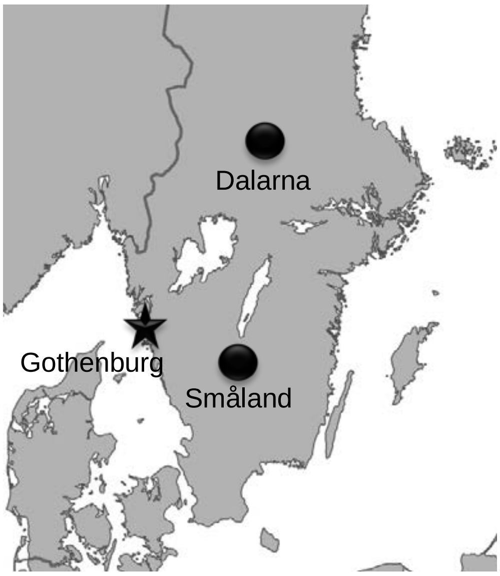

Figure 5. The plant and sourcing locations.

Table 2. Base scenario characteristics

	Characteristics
Train	20 wagons (type Sgns), an electric engine (type Rd), 60 45m^3 load units with rotary unloading, 2 100 MWh of logging residue chips, or 1 750 MWh of bark.
Terminal	Electrified rail track in Småland with no diesel shunting. Diesel shunting in Dalarna. At both terminals the fuel is handled by wheel loader and the loading time is 4 hours.
Road haulage	Road transport to the terminal is 40 km by wood chip container truck carrying 93 MWh. Chipping takes place road-side in the forest for the wood residues. The bark requires no further chipping.
Plant	Diesel shunting to the plant. Unloading by a heavy forklift truck with a rotator. Unlading time is 4 hours.

The cost per MWh for the analysed system is 99.95kr/MWh. This includes all activities, including chipping, road transport, terminal handling, etc. See Figure 6 for the cost allocation. Noteworthy are the high costs associated with chipping, train transport, and the sending terminal. The cost for the rail part is 35.18kr/MWh (shunting, rail transport, and load units).

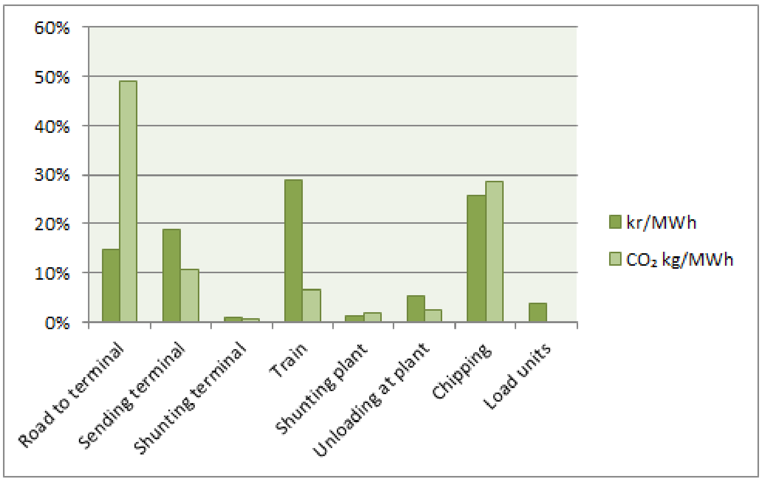

Figure 6. Costs and emissions in the base scenario.

From an environmental perspective, the CO_2 emissions are 2.92 kg per MWh transported. The major sources are the road transport and chipping. Noteworthy is the low CO_2 emission from the train transport, as a consequence of the clean Swedish electricity mix.

4. Results

A number of potential scenarios were evaluated. The following section divided the results according to the five stages used in the supply chain description: Pre-haulage, Terminal, Long-haul (Rail), Post-haulage/delivery, and System. If nothing else is stated in the scenarios, the assumptions and variables are the same as in the base scenario.

4.1 Stage 1 Pre-haulage

Distance to terminal

The road haulage to the terminal constitutes a large cost in the system. A haulage distance of only 10 km cuts the cost by 11%, while a distance of 100 km increases the cost by 22%. This shows the importance of keeping the haulage distance to the terminal short. See also section 4.4 for a further analysis about haulage distance.

4.2 *Stage 2 Terminal*

Terminal costs

Terminals are used for transhipment and storage, and this study shows (see discussion in the Appendix A concerning terminal input data) that the terminal costs can vary significantly due to operating practices and commodities handled at the terminal. Many companies also use existing round wood terminals for biofuel; in many cases these are old and the investment is already written off. Biofuel is perceived as a low-marginal product at the terminal and companies state that biofuel is often only charged a marginal handling cost. Assuming that the road-rail terminal cost could be lowered to only the variable costs of 10 kr/MWh, or roughly representing the costs of two handlings with a wheel loader, this would result in a 9% reduction of system costs. On a more general level, this is particularly interesting in a comparison with all-road transport, as a significant share of all-road transport volumes already pass through a terminal (Björklund and Eriksson, 2013). Values range from 20% to 60% for individual companies (Enström, et al., 2013). For an operator considering switching from all-road transport to multimodal transport it should be noted that not all terminal costs in the base scenario are added costs: some are probably already incurred in an all-road system.

Shunting efficiency

Shunting costs are hard to estimate as they are very situation-dependent for each terminal. Bäckström et al. (2009) surveyed the shunting at a number of Swedish conventional intermodal terminals and found that the time for shunting ranged from 20 minutes to 1 hour, not including administrative tasks and break tests. Assuming that the shunting at both the plant and terminals could be cut to a minimum amount of time with all equipment available at the terminal and minimum administration, this could result in a system cost reduction of 1% or 3% for the rail part (shunting, rail transport, and load units). A way of reducing the cost for shunting is to use the electric long haul engine. This removes the need for a separate diesel shunting engine but requires a special track layout and an electrified line. Electrified shunting reduces the costs by 0.4% for the system or 1% for rail. In comparison, assuming diesel shunting at all locations in the base scenarios increases the costs by 0.3% for the system and 1% for rail.

Chipping

The chipping position in the supply chain potentially has a large impact on transport costs. Chipping costs can be lowered by chipping at a terminal, but this comes at a cost for more expensive road transport due to the low density of logging residues. Changing the chipping location for the wood residues to the terminal results in a 1% reduction in the base scenario. See Figure 7. However, this is very dependent on the distance to the terminal. If the distance is doubled to 80 km for the logging residue part, the costs are increased by 17%. From an environmental perspective, chipping at the terminal releases less CO_2, but this is outweighed by less efficient road transport, resulting in a total increase in CO_2 emissions of 21% for the first scenario and as much as 77% for the 80 km haulage.

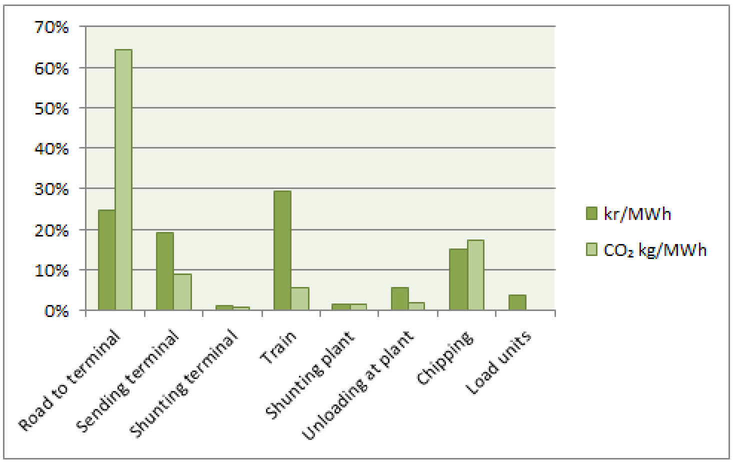

Figure 7. CO_2 emission and costs distribution when chipping at the terminal.

The importance of the chipping location is made clearer by examining a system with only logging residue chips. Assuming that the bark in the base scenario is replaced by logging residue, a comparison has been made between road-side chipping and terminal chipping, depending on road distance to the terminal. A break-even point between the chipping methods can be found at 48 km road haulage, after which road-side chipping gives a lower cost (see Figure 8).

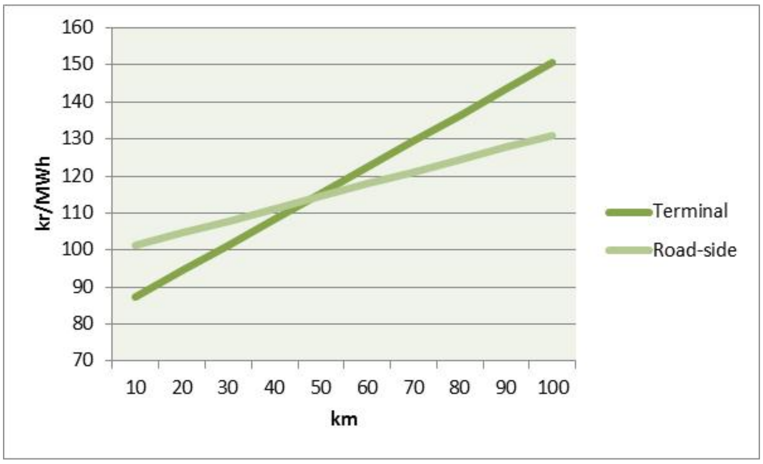

Figure 8. Break-even point between road-side chipping and terminal chipping.

The chipping equipment at the terminal gains its cost advantage by being larger, but therefore also requires larger volumes. Note that since about 80% of a pile of logging residues is air and space at the terminal is limited, it is important to chip the logging residue when it arrives to avoid filling the terminal. In comparison, 1 MWh of wood residue takes up 3.5 m^3, while 1 MWh of logging residue chips only take up 1.3 m^3. Wood chips can also be piled higher, thus making more efficient use of each m^2.

The calculations assume that the fuel in both cases must pass a terminal, thus incurring the terminal costs. The break-even distance would be shorter in an all-road system, where the option to chip roadside also means that the terminal cost could possibly be avoided. A special case is round wood, as this almost always is sent to a terminal for chipping since most HPs are not allowed to chip at the plant. This makes these flows attractive from a multimodal point, since they already incur the terminal cost. Round wood also has a high density and thereby lower transport costs. Assuming both the bark and logging residues in the base scenario are replaced by round wood that is transported by a timber truck and chipped at a terminal brings a 14% cost reduction. If, assuming that the biofuel would only be charged the marginal cost for the terminal operations of 10 kr/MWh, the cost would drop by 23%. Note that the price of the wood biofuel is not included, which might differ between logging residues and round wood.

4.3 Stage 3 Long haul (Rail)

Type of rail engine

The choice of rail equipment has a significant effect on cost. Changing to older equipment (RC4 engine and older used Lgns wagons) results in a system cost reduction of 4% and a rail cost reduction of 12%. Due to weight restrictions on the wagons, this system carries slightly less biofuel (9.6 GWh per week). Operating with old equipment also increases the risk of technical failures and disruptions. A safer system can be achieved by operating more modern engines. A new modern engine - e.g., TRAXX equipped with ERTMS - brings a cost increase of 4% and 10% for system and rail, respectively. The TRAXX is also a stronger engine and can pull heavier trains. Utilising maximum load capacity (15.2 GWh per week) results in a system cost reduction of 17%. The use of the more expensive engine can balance out against the increased loading capacity; however, such a large and heavy train cannot operate on all tracks and terminals, making this dependent on whether or not the extra capacity is needed and can be utilised.

Utilisation of rail engine and wagons

Of particular importance is the utilisation of the rail engine. A rail engine has high fixed costs, and higher utilisation brings a lower cost per hour. Assuming that the rail engine could find full employment outside the base scenario (i.e., weekends and summers), this would result in a reduction of system costs by 3% and 9% for rail. If both engine and rail wagons could be used similarly outside the system, the cost would reduce by 7%. For the rail part, this would be a 19% reduction. If it is further assumed that the load units could also find another use, the costs go down by 9% and 26%, respectively. Naturally, this is an extreme example, as a 100% utilisation of the resources outside the system is not practically possible; however, it shows the importance of a high degree of utilization. Current operators state that they can find no use for wagons and load units during the summer months, but that the engine often has some alternative use.

Train length

As in all rail systems, larger trains bring lower costs per transported unit. The effects of train size on the current base scenario can be seen in Figure 9. Current infrastructure and regulations do not allow larger trains, but this has been disregarded in the calculation as there are ongoing discussions in Sweden to allow longer trains (Trafikverket, 2015). However, extra engines have been added when necessary to be able to pull heavy trains. The peak in the curve represents one extra engine.

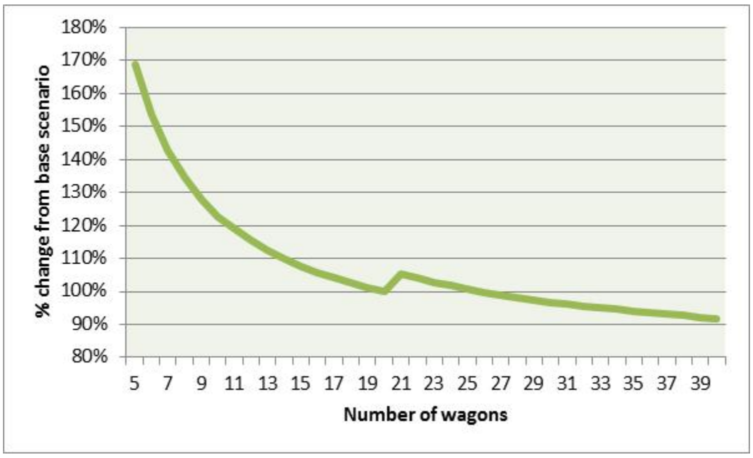

Figure 9. The effect of train length.

Fill rate on train
Rail transport is an inflexible mode of transport, where timetables are set long in advance and possibilities of deviations are limited. However, the fuel demand can vary depending on the outside temperature. The plant can operate at as low as 30% capacity before having to shut down for technical reasons. The demand reduction can be handled by either running the trains as normal, but loading less fuel, or by cancelling some trains. The characteristics of rail transport - with planning and contracts made long in advance, combined with the unpredictable weather and demand for heat - make most current rail set ups operate according to the first principle (or, if possible, redirecting to a different destination/customer) (see Figure 10). System costs increase by 36% when the train is 50% full. Looking only at the costs for the rail part (shunting, train, and load units, but not loading/unloading), the costs increase by 87%.

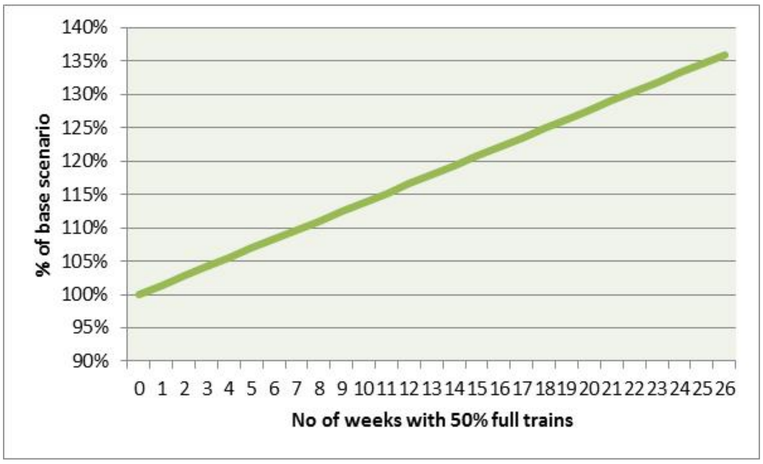

Figure 10. Increasing costs based on number of weeks with 50% full trains.

Type of load unit
There are many different types of load units that can be used for transport, as discussed in Flodén (2015). One of the most common types of load unit used for biofuel transport is the traditional 40m^3 wood chip container. The 40m^3 container has less efficient unloading than the rotary container, thus extending the unloading time. Unloading from the train is normally made by a smaller forklift truck and the container is emptied by transferring it onto a hooklift truck that tips the container. The extra handling of transferring the container to the hooklift truck increases the unloading time. In the rotary system, the truck turns the container upside-down with a rotator attached to the fork-lift truck and empties it directly. Average unloading of a rotary container is around 4 minutes, compared to around 7-8 minutes for the container system (Enström and Winberg, 2009). This impacts the turnaround time of the train as it extends the unloading time of a full train to 7-8 hours as compared to 4 hours and thereby limits the utilisation of the train and terminal. This could be particularly troublesome for a very large plant that requires several trains per day. Loading capacity on the train is reduced to 8.7 GWh per week, resulting in a 4% cost increase. However, the smaller loading capacity reduces the train weight and also makes it possible to increase the number of wagons on the train to 22 without exceeding the maximum train weight. This makes it possible to deliver 9.6 GWh, which is close to the base scenarios of 9.8 GWh, at a 2% cost increase.

The impact on the rail costs for the longer unloading time depends largely on cycle time for the train. In most cases, the train runs on a 24 hour cycle with one delivery per day, constrained by the opening hours of the plant and terminal. Unless the transport distance is very short, it is not possible to make two cycles per day. As long as the extra 4 hour unloading time does not impact the 24h cycle, or prevents the train from making two runs per 24h cycle, the train costs will remain largely unchanged (exact costs will depend on the timetable). However, as in the current case, if the longer unloading time makes the run to Dalarna impossible the cost will increase significantly. Assuming that the run to Dalarna is impossible and the train stands idle, the costs increase by 18% for the 40m^3 system with extra wagons.

The cost for the fork lift truck is significantly less for the smaller truck used in the 40m3 system. The fixed truck costs are about 3-4 times higher for the rotary system, making a high utilisation of the trucks important as the fork lift trucks are stationed at the plant. However, the smaller truck in the 40m^3 system needs a hooklift truck for unloading, but these are available on the open market and can be contracted per hour. The break-even point between the unloading costs of two systems are at around 4 trains per week if operating half the year with trains of similar loading capacity and carrying only logging residue chips. See Figure 11. Note that this only refers to the unloading process and not the total system.

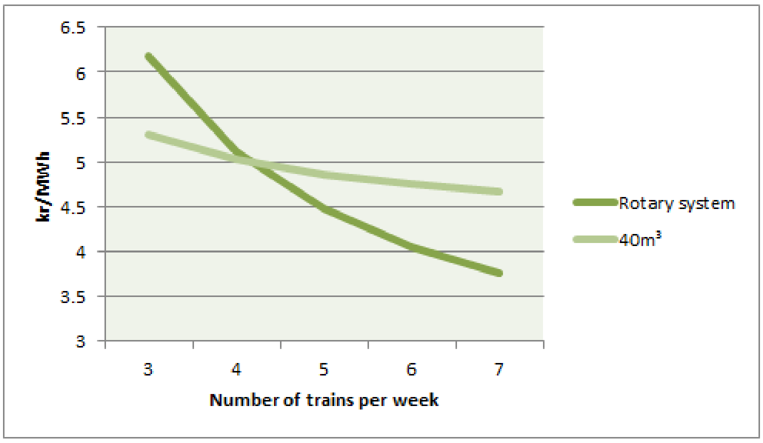

Figure 11. Unloading costs for rotary system and 40m^3 using hooklift trucks.

A system comparison was made assuming a 300 km transport with logging residue chips, with the same characteristics as the break-even calculation above: 40 km pre-haulage and train delivery at the plant. This shows that the rotary system gains competitiveness as the utilization increases. See Figure 12.

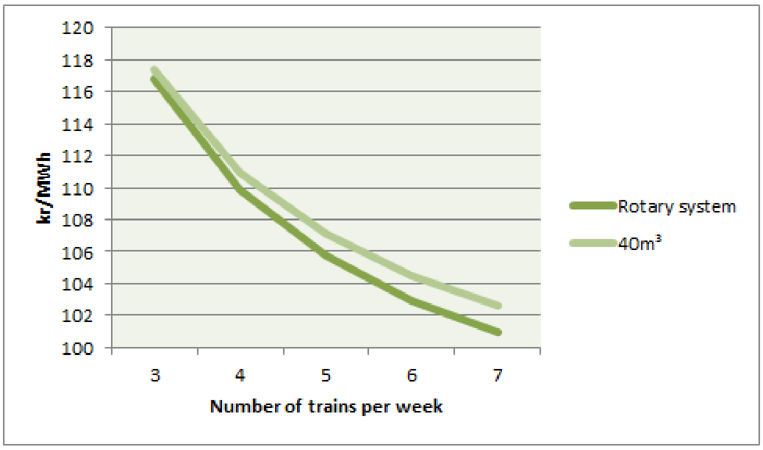

Figure 12. Comparison between a 300 km transport with rotary system or 40m^3 containers.

4.4 Stage 4 Post-haulage/delivery

Via receiving terminal
In the base scenario, the train runs directly into the plant. However, most plants lack direct rail access and require a separate terminal with haulage by road for the last part to the plant, resulting in a 23% cost increase (see Figure 13). This assumes a terminal with diesel shunting located 20 km from the plant and road haulage by wood chip truck carrying 103 MWh logging

residue chips or 72 MWh bark. The train is unloaded by a forklift truck with a rotator and loaded to the truck by a wheel loader.

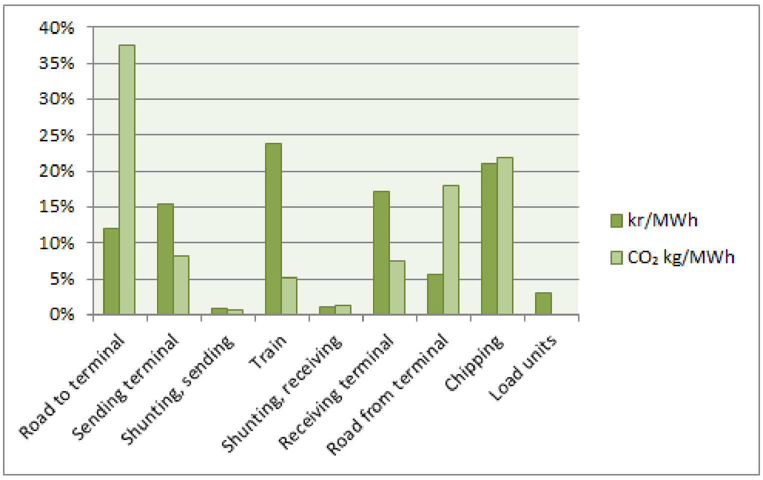

Figure 13. Distribution of costs and CO_2 emissions with pre and post-haulage.

Distance from terminal

As with the haulage cost to the terminal, the distance from the terminal to the plant is also important. A 10 km haulage increases the cost by 19% and a 50 km haulage by 50%. The importance of keeping the haulage short to and from the terminals is further highlighted by looking at the combination of long and short haulage distances in both ends. A 10 km haulage in both ends gives an 8% cost increase, while a 100 km haulage gives an increase of 72%. This very high cost increase clearly shows the need to keep the distance short. See Figure 14.

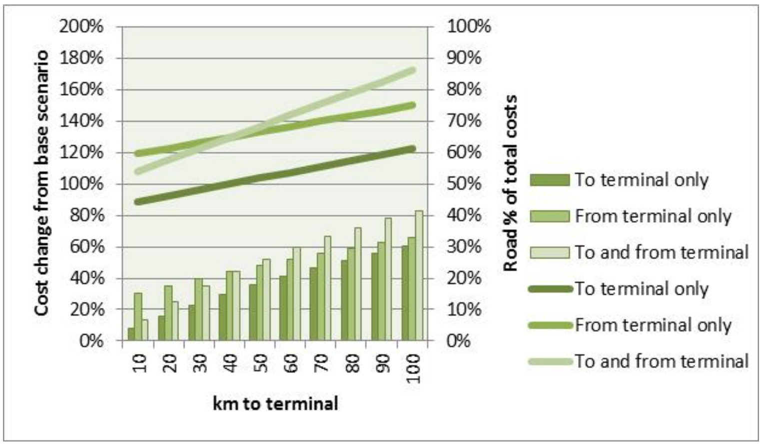

Figure 14. Effect of changed road distance to and from terminal. The lines represent the change in total costs and the bars the road's share of total costs.

Intermodal container transport

An intermodal system includes the transhipment of a detachable load unit between road and rail, thus transporting the fuel in the same load unit all the way to the plant. The advantages of transferring the load units is more efficient transhipment at the terminal and that conventional intermodal terminals can be used. The drawback is that the loading capacity on the train is reduced as it is limited by the maximum allowed weight on the road. Also, more load units are needed since they are also used for the transport from the forest and for storage at the terminal while waiting for the train. If there is road haulage in one part of the chain then there is a need for at least double the number of load units on the train so there are load units ready to be loaded on the train, or the trains dwell time must be significantly increased. Consequently, the need is tripled if there is road transport at both ends. However, to maximize the transport from the forest there might be a need for even more containers. Each container truck normally uses six containers. When three full containers are picked up in the forest, three empty ones are dropped-off. By the time the truck has delivered the fuel and returns with empty containers, the containers in the forest have been filled and are ready for pickup. This minimizes the waiting time for the truck and maximizes the use of chipping equipment, etc. in the forest, but requires extra containers. This further depends on if it is possible to unload the empty container from the truck in the forest. Hooklift trucks can perform the unloading themselves, while other trucks and load units, including rotary containers, require external equipment such as fork lift trucks. These are not available in the forest as they are too large and heavy for narrow forest roads; therefore, the system loses some of its effectiveness as it turns into a "hot" system that requires the simultaneous presence of both the truck and the chipper (or other loading equipment if the fuel is already chipped).

If intermodal transhipment is used in the base scenario at the terminal, the cost remains almost the same, with a 1% reduction. Looking at the different costs, the road haulage costs increase by 22% and the load unit costs by 100% (see Figure 15). However, the terminal costs decrease by 42%, which balances out the increased costs. Note that the terminal costs assume a conventional intermodal road-rail terminal that has high efficiency in transhipping containers. If a forest terminal is used for the container transhipment, the costs will likely be higher since the equipment utilization and experience in container handling will be lower. Terminal design is also not adapted to container handling. Road transport with the rotary containers is further constrained in that they exceed the maximum width allowed on the road and therefore require a special permit (Flodén, 2015). Extra costs and administration for this have not been included, nor have any extra costs in the forest due to the "hot" system. The true cost of the intermodal system is therefore probably higher. The high road transport costs also make the system more sensitive to longer haulage distances (see Figure 16). The higher road cost is caused by the decreased loading capacity per truck, as only two rotary containers can be carried per truck without violating maximum weight restrictions on the road.

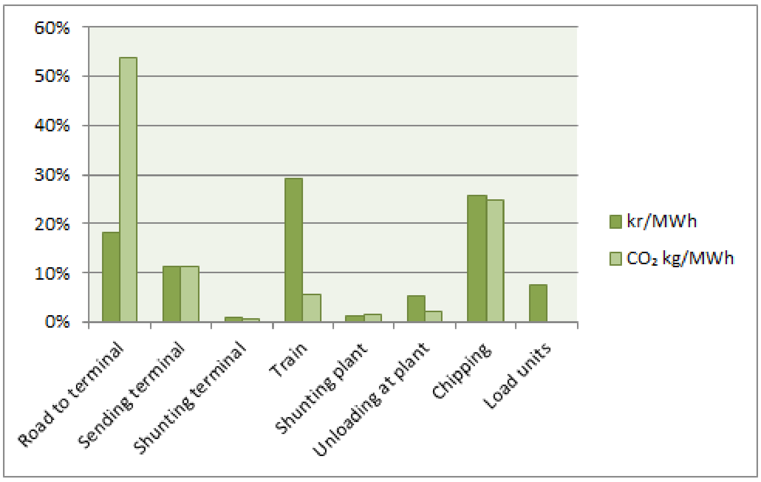

Figure 15. Distribution of costs and CO_2 emissions with intermodal transhipment for the base scenario.

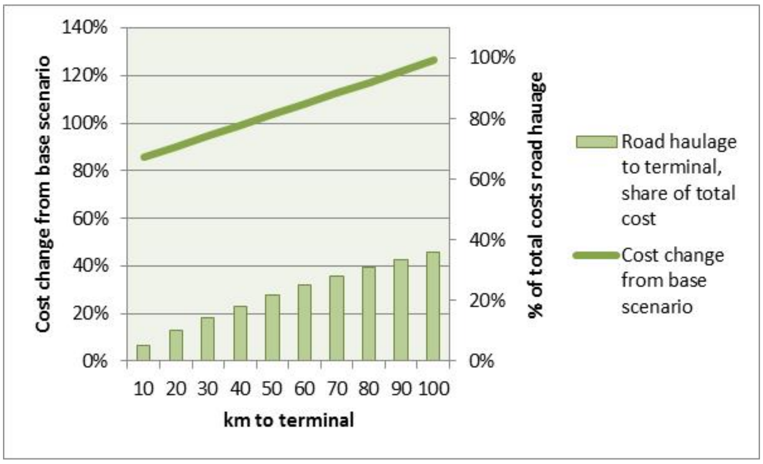

Figure 16. Effect of changed road distance to terminal with intermodal transhipment for the base scenario.

Similar results are found for the 40m³ system with an increased number of wagons, at a 1% cost increase. See Figure 17. In this case, the road transport costs are mainly unchanged, while the terminal costs are further increased due to the increased number of load units.

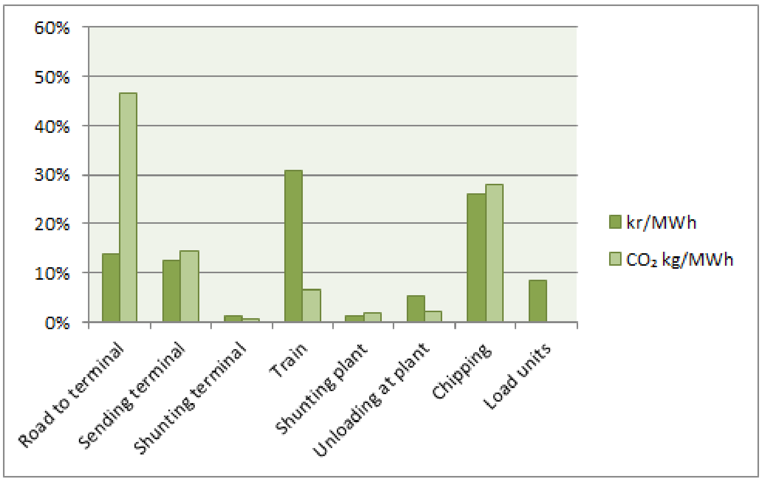

Figure 17. Distribution of costs and CO_2 emissions with intermodal transhipment for 40m³ system.

An interesting case is to only use intermodal transhipment in the receiving end of the chain. The transport from the forest into the sending terminal is already well established and efficient. In cities there is often no terminal suitable for bulk transhipment of biofuel; however, there is often conventional intermodal terminals suitable for container transhipment. Being able to use conventional terminals will therefore increase the number of possible terminals and thereby potentially reduce the road haulage distance between the terminal and the plant. In the current case there is a conventional intermodal terminal 6 km from the plant. Further, the needs for load units are reduced since there is no need for extra load units for the forest operations. This system gives a cost increase of 12%, or 16% for the 40m³ system. Terminal handling costs are higher for the 40m³ system, since more load units are required and the rail transport costs are higher. The road transport costs and load units costs are lower, but this does not fully balance the higher train and terminal costs.

4.5 Stage 5 System

Return flows

Biofuel trains normally run empty on the return trip. Assuming full return flows in the rail system reduces the cost by 17%, the cost for the rail system is reduced by 50%. This assumes that the train is completely filled on the return, using the same load units and terminals, and that no detours are required. This is, of course, not realistic, but shows the maximum effect of gaining return flows. Return flows might also exist on the road side. If the road haulage trucks receive full return flows, then the costs are reduced by 7%. Full return flows on both trucks and train reduces the costs by 25%. Naturally, the possibility of return flows also exists in an alternative all-road transport system and would have a similarly large impact. An all-road system also has trouble finding return flows, but to a lesser extent as it is not dependent on finding one large return flow and is more flexible.

Round trips per week

Changing the overall train utilisation has a large impact. The base scenario assumes operations five days per week. Assuming that the train could only operate three days per week to Småland results in a 17% cost increase. Similarly, assuming that the train would operate 7 days per week reduces the cost. An extended case is constructed assuming that the base case is complemented with two shorter runs on Saturday and Sunday to Varberg, 78 km south of Gothenburg. The studied HP has access to a terminal at the port of Varberg and occasionally imports fuel by ship. Costs for the ship and chipping are not considered. The extended scenario delivers 14.0 GWh per week at a 23% cost decrease. The effect of extending the operation to 7 days is particularly large since in the base scenario calculations assume that trains stand idle during the weekend

Length of season

Train utilisation is also affected by the length of the season during which the train operates. Assuming that the train could operate all year would reduce the costs by 8%. This would not be realistic due to the limited need for heat during the summer, but even an extension of the season by one month would reduce costs by 2% (see Figure 18). The extension could also be made possible by taking other complementing goods to nearby locations or increasing the summer storage at the plant. Note that an important factor in these calculations is how much outside use the train set has, particularly when operating only a few weeks in this system

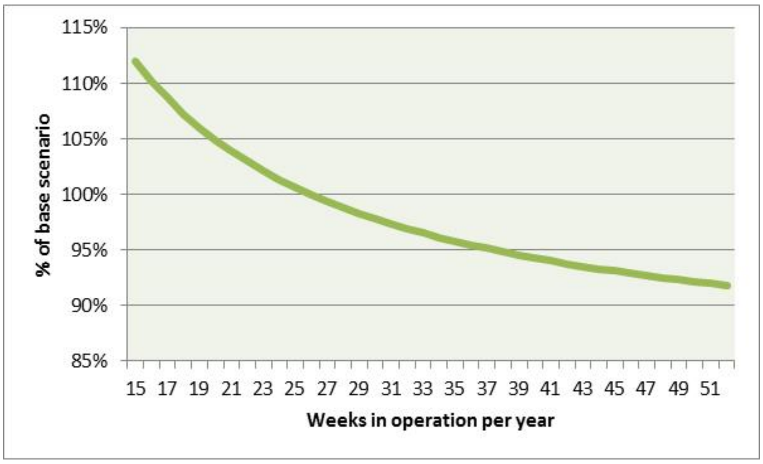

Figure 18. Length of season and costs.

Type of biofuel

Different types of fuel have different densities and energy content per tonne, thus resulting in different transport costs. Calculations have been made based on the base scenario, but with the same fuel on all trains and the maximum train capacity. The rail costs include rail transport, shunting, and load units. The most expensive fuel to transport is sawdust, which has a low energy content. The different types of wood chips all have similar costs. See Figure 19.

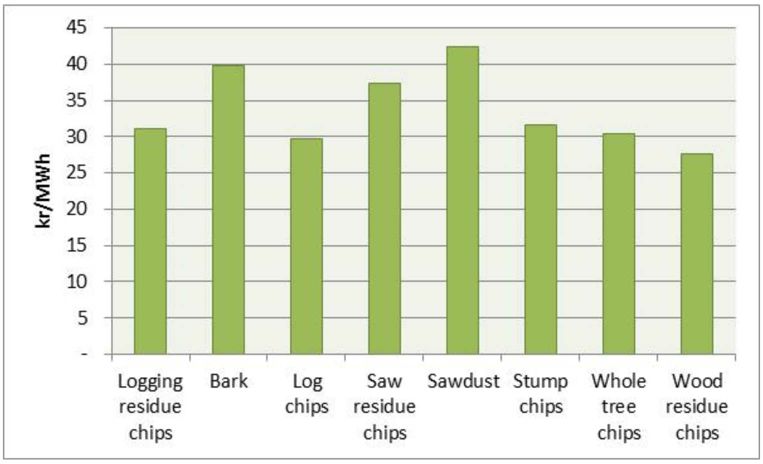

Figure 19. Rail costs for different fuels.

4.6 Summary of case results

The tested cases are summarised in Table 3. The table is sorted according to cost, and an approximate break-even distance with road is given based on a wood chip truck with logging residue chips, roadside chipping, and where 40% of the flow is transhipped at a road-road terminal. This is the same assumption as when the break-even between road and rail was previously calculated. As can be seen, the cases with a high utilisation of resources give the lowest costs. Cases with long road haulage distances and more use of terminals give the highest cost.

Table 3. Summary of results

	System		**Rail**		
Name	**Cost % of base scenario**	**CO_2 % of base scenario**	**Cost % of base scenario**	**CO_2 % of base scenario**	**Break even distance road, km**
1 Full returnload, train and trucks	-25%	-28%	-49%	-36%	97
2 Seven days per week	-23%	-25%	-25%	-15%	102
3 Round wood chipped at terminal with low costs	-23%	-20%	-9%	-12%	104
4 Full returnload, train	-17%	-3%	-49%	-36%	121
5 New rail engine and extra wagon	-17%	-24%	-10%	-14%	122
6 Roundwood chipped at terminal	-14%	-20%	-9%	-12%	133
7 Base scenario 10km road haulage to terminal	-11%	-37%	0%	0%	142
8 High utilisation, engine, wagons and load units	-9%	0%	-26%	0%	148
9 Low terminal cost	-9%	0%	0%	0%	149
10 52 week utilisation	-8%	0%	-19%	0%	151
11 Full returnload, trucks	-7%	-25%	0%	0%	154
12 High utilisation, engine and wagons	-7%	0%	-19%	0%	156
13 Old engine and wagons	-4%	0%	-12%	-3%	166
14 High utilisation, engine	-3%	0%	-9%	0%	167
15 30 week utilisation	-2%	0%	-5%	0%	171
16 Chipping at terminal	-1%	21%	0%	0%	174
17 Efficient shunting	-1%	-1%	-3%	-7%	175
18 Rotary container with intermodal transshipment	-1%	16%	10%	0%	175
19 Electrified shunting	0%	-2%	-1%	-24%	177
0 Base scenario	**0%**	**0%**	**0%**	**0%**	**178**
20 Diesel shunting	0%	1%	1%	10%	179
21 40m^3 container, intermodal transshipment with extra wagons	1%	5%	21%	2%	183
22 40m^3 container, swtich body truck at plant extra wagons	2%	0%	4%	2%	184
23 Modern rail engine	4%	0%	10%	0%	190
24 40m^3 container, swtich body truck at plant	4%	1%	9%	6%	191
25 Road haulage in both ends, 10km	8%	-18%	0%	0%	205
26 Via intermodal terminal in Gothenburg, 6km	12%	-2%	10%	0%	218
27 Chipping at terminal, 80km haulage	17%	77%	0%	0%	233
28 Three days per week, Småland	17%	8%	9%	-32%	235
29 40m^3 container, swtich body truck at plant extra wagons, no Dalarna	18%	8%	14%	-31%	237
30 Via intermodal terminal in Göteborg, 20km	19%	-2%	10%	0%	239
31 Via terminal Göteborg, 10km haulage to terminal	19%	19%	0%	0%	241
32 Base scenario 100km road haulage to terminal	22%	74%	0%	0%	251
33 Via receiving terminal, Gothenburg	23%	31%	0%	0%	252
34 Via terminal Gothenburg, 100km haulage to terminal	50%	125%	0%	0%	343
35 Road haulage in both ends, 100km	72%	198%	0%	0%	415

4.7 Best feasible case

The best options from the calculations above have been combined into a best feasible scenario representing a realistic combination of the options analysed given the conditions in the current case. Table 3 has been used to identify the most promising options where the option giving reduced costs have been further examined for feasibility. See the summary in Table 4.

Table 4. Feasibility of scenarios

Scenario	Feasibility
Full return load, train and trucks	Unlikely to receive full return load everywhere.
Seven days per week	Would result in too much fuel to the HP.
Roundwood chipped at terminal with low costs	Realistic option to source round wood and select an efficient terminal.
Full return load, train	Unlikely to receive return load.
New rail engine and extra wagon	Would result in too much fuel to the HP due to the extra capacity.
Roundwood chipped at terminal	See above.
Base scenario 10 km road haulage to terminal	Unlikely that sourcing distance can be significantly shortened from today, although pre-haulage can be avoided by sourcing directly from a wood processing industry with rail access.
High utilisation, engine, wagons, and load units	Not likely to find use for the load units outside the system as they are specialised.
Low terminal cost	See above.
52 week utilisation	Not realistic to run the system all year.
Full return load, trucks	Unlikely to receive return load back to the forest.
High utilisation, engine and wagons	Use of outside biofuel transport cannot be influenced by the biofuel system.
Old engine and wagons	Not appropriate due to reduced reliability.
High utilisation, engine	Use of outside biofuel transport cannot be influenced by the biofuel system.
30 week utilisation	Not realistic, although it could be possible to extend the season a few weeks, e.g., by building storage.
Chipping at terminal	A realistic option for large terminals, in particular in combination with round wood.
Efficient shunting	A feasible option to improve shunting efficiency.
Rotary container with intermodal transhipment	Not suitable as this requires special permits for road transport at a very small cost reduction since rail access exists at the HP.
Electrified shunting	Not available at most terminals and requires infrastructure investment (power lines).

The selected scenario operates 5 days per week with rotary containers delivering round wood chipped at terminals in Småland and bark loaded directly at a rail siding from the wood processing industry in Dalarna. The fuel is delivered directly at a rail siding at the HP. A slight increase in the length of the season by two weeks to 28 weeks is assumed. Other aspects of the scenario remain as in the base scenario. The best case scenario gives a cost decrease of 22% with CO2 emissions of 1.79kg/MWh. See Figure 20. A rough break-even point against all-road transport is at 106 km.

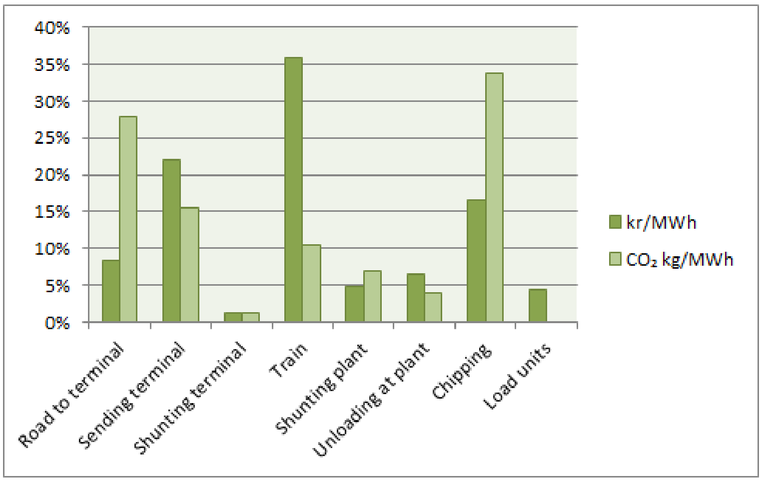

Figure 20. Distribution of costs and CO_2 emissions for the best case scenario.

A low cost system should first have a high utilization of resources. A system operating 7 days per week would deliver 14.0 GWH, or 82%, of the plant's need at full power. Considering that the plant does not always operate at full power and the risks associated with depending too much on one train, it is considered appropriate to choose a 5 day per week operation, as in the base scenario. A more modern rail engine would increase the loading capacity on the train and thereby lower the costs. However, considering the current infrastructure, such large trains are considered unsuitable. Also, the delivered volumes would increase to 15.2 GWh per week, or 89% of the plant's need at full power. An older engine with old wagons would also decrease costs, but at a higher risk of technical failures and disruptions. The older engines are therefore not selected due to the need for a reliable system. The rotary containers are considered the most effective and are selected. Return flows would also reduce the costs, but are considered very hard to get and are therefore not included. Road haulage distances should be kept as short as possible. However, for this scenario it is assumed that the distance in the base scenario remains the same, as this is the average distance today. Several actors in the wood processing industry have rail access at their plants. Selecting to source from an actor with rail access could lower the transport cost. Chipping round wood at the terminal has shown to be very efficient and is selected instead of logging residue chips for Småland. Increased utilization of the train set outside the system would further decrease the costs, but it is hard for the power plant to influence this decision. However, extending the season for the train could be possible, but would largely depend on the outside temperature, which is impossible to predict.

The best case scenario can be further extended with a focus to reduce CO_2 emissions. The emission in the best case solution mainly relates to the chipping and road haulage. The chipping emission can potentially be reduced by replacing the diesel powered chipping by electric powered chipping. A switch to electric chipping would not only reduce the emissions but also the costs, assuming a high utilization of the chipper. In the best case scenario, costs would be reduced by 32% and emissions to 1.18 CO_2 kg/MWh by electric chipping at the terminal. However, very few terminals would have the volumes required for an electric chipper. The emissions could also be further reduced by alternative fuels and by trying to keep road haulage as short as possible. Diesel powered shunting should, as far as possible, be replaced by electric shunting and excess shunting should be avoided, for example, by extending rail siding so that the trains do not have to be split.

The studied HP has rail access at the plant, but for plants without rail access an intermodal or multimodal solution is required. For an intermodal transport solution where the same load units are transhipped through the chain, it is advisable to avoid bringing the load units all the way into the forest. This requires several extra load units or interferes with an already effective system.

Also, if larger units, such as the rotary containers, are used, there is also a practical issue of limited space for handling and marshalling load units at the roadside and possible extra handling equipment needed. A better option is to use bulk loading at the sending terminal and bringing the containers all the way to the plant at the receiving end. This comes at an increased cost compared to train deliveries directly to the plant (19%), but less than if bulk transhipment is used at the receiving terminal (23%). The cost advantage can be further increased if the conventional intermodal terminal is closer to the plant than the bulk terminal. This is also likely since there are more conventional intermodal terminals in and around the cities than bulk terminals. Note that this assumes that the rotary containers are transported by road, which requires a special permit. Also, the terminal costs are very important here. An efficient bulk terminal, in comparison with a less efficient conventional intermodal terminal, easily gives the bulk option the lowest cost.

5. Analysis

Ultimately, the competitiveness of intermodal transport depends on where the fuel can be sourced and at what price. Either the plant is so large that fuel cannot be sourced locally and it must be sourced far away, and/or type of fuel and price variations between regions makes it possible to find a better price of fuel from a faraway region. However, a properly designed multimodal transport system can shorten the break-even distance and make multimodal transport competitive on shorter distances, which is desirable due to the lower emissions from multimodal transport. A 10% cost change in the base scenario equals an approximately 33 km shift in the break-even distance. A successful multimodal transport system for biofuel must meet the five key logistics challenges identified by Awais and Flodén (2014): seasonal variability, storage, chipping, low density, and dependency on political policies. The challenges are discussed in the following text and summarised in Table 5.

5.1 Seasonal variability

Rail as a transport mode requires large volumes and a high utilisation of the equipment to be economically efficient. Also, the need for transhipment and road haulage to/from terminals makes it impossible for multimodal transport to be competitive for smaller plants that can source all their fuel locally with a short road transport. Only the larger plants may therefore be candidates for multimodal transport. The plant studied in this case at 17 GWh/week is on the smaller size for multimodal transport, because the seasonal variability often does not operate at full power, thus requiring less fuel. Multimodal is attractive for the plant when operating at full capacity but, e.g., a 50% full train increases the costs by 36%. The seasonal variability also poses a challenge for road transport, but to a less extent due to the more flexible road system where capacity can be more easily adapted and outside transport assignments more easily found. To overcome the seasonal variability, multimodal transport must be applied at large plants where the train can be run at full capacity during most of the season. The effects can also be reduced by intensifying attempts to find alternative uses for the equipment outside the season.

5.2 Storage

Storage is often performed at the plant or at the terminals. The use of storage at terminals is an advantage for multimodal transport. In a comparison with an all-road system it is important to remember that several activities are performed both in an all-road system and in a multimodal system. For example, a large share of the all-road volume already passes a terminal, and in some cases a terminal with rail access. Values range from 20% to 60% of the flows for an individual company to pass a terminal (Enström, et al., 2013). Therefore, these flows already incur a terminal cost, which makes the additional terminal cost low for loading the fuel on a train instead of on a truck at the terminal. Multimodal transport is thus more competitive against flows that already pass a terminal. This is particularly true for round wood, which almost always passes a terminal.

Terminal activities are associated with large costs. It is important to note that the costs associated with in particular terminals can vary significantly. A very wide range of cost estimates are found in the literature and in interviews with industry representatives. Thus, selecting the right terminal is a key issue for a successful multimodal system. A related issue is also how the costs at a terminal are shared between different types of wood using the same terminal, e.g., pulp wood and biofuel.

5.3 *Chipping*

Chipping is most often performed road-side in the forest. However, whenever possible, multimodal transport should try and utilise potential cost savings from using a terminal, such as the lower chipping costs at a terminal compared to road side chipping. For shorter pre-haulage distances, logging residues should be brought to the terminal and chipped there, preferably with an electric chipper.

5.4 *Low density*

The low density of biofuel points to the importance of keeping the transport costs low. It can be concluded that a high utilisation of the resources is the most important aspect in keeping the costs down. Also, road distances to and from the terminals should be kept as low as possible. In particular, the very long pre/post-haulage distances of 80-100 km gives very high costs for the system. Options with rail access directly at the plant or directly to a forest industry are preferred. For example, adding a terminal in the receiving end and 100 km road haulage to the plant increases the cost twice as much as the cost savings gained from finding full return loads for both trains and trucks in the base scenario. Thus, avoiding terminals and keeping road distances short is the most important aspect. Fuels that can be picked up directly at a terminal without road haulage have the greatest potential, for example forest industry by-products from industries with rail access. Multimodal transport also becomes more competitive against road transport as the weight of the fuel increases. Road transport of biofuel is restricted by weight, while rail transport is restricted by volume. Thus, multimodal transport should focus on the heavier types of biofuel to increase its competitiveness.

5.5 *Political policies*

Policies impact the multimodal biofuel system on three levels: local, industry, and national. On a local level, the plants are often municipality owned and subject to political regulations. Multimodal transport would be favoured by political instructions for the plants to place a higher importance on CO_2-emissions and to pay more for transport with lower emissions. Currently, most plants have no specific requirements on transport emissions. Also, local permits, such as whether or not night-time deliveries are allowed, impact the system and its flexibility. Since multimodal transport is, by its nature, less flexible, flexible local regulation improves the system flexibility and thereby its competiveness.

On an industry level, political policies impact the competitiveness of the industry as a whole; e.g., by taxing non-renewable energy, electricity certificates, etc. Reduced competitiveness for the industry brings down the fuel volumes needed, making it harder for multimodal transport. Policies in favour of biofuel are therefore also beneficial for multimodal transport.

On a national level, political decisions also impact the general competitiveness of transport modes; e.g., the level of road taxes, fuel taxes, infrastructure fees, etc. Any political incentive in favour of multimodal transport in general will naturally also positively impact the potential for multimodal biofuel transport.

6. Conclusions

The possibilities for multimodal transport to overcome biofuel logistics challenges are summarised in Table 5.

Table 5. Logistical biofuel challenges and the multimodal options

Challenge	Multimodal options
Seasonal variability	Focus on large plants to fill the train all season.
Storage	Utilise the multimodal terminals and focus on flows that already pass a terminal. Select an efficient terminal.
Chipping	Utilise the lower chipping costs at the terminals.
Low density	High resource utilisation. Short pre-/post-haulage distance by road. Pick-up/deliveries directly to the plant.
Dependency on policies	Influence local and national politicians for flexible regulations and support for multimodal transport.

Further, the competitiveness of multimodal transport can be improved by finding alternative sourcing locations where lower fuel costs can be obtained, rather than by sourcing locally.

It is evident that multimodal transport is a system requiring large volumes and high resource utilisation. A potential for multimodal transport of biofuel exists for the larger plants sourcing from long distances, but multimodal transport is not competitive for smaller plants with shorter sourcing distances. Load units maximising the volume on rail are found efficient, although it is not efficient to utilise the same load unit all the way from the forest. A further challenge is the inflexible nature of multimodal transport, which requires long term planning and more complicated logistical setups.

This study also presents open cost data in the Appendix that can be used for further studies.

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Appendix A

Input data

Table 6. Truck

	Wood chip container truck	Wood chip truck	Forest residue truck	Timber truck	Source / Comments
Purchase price	2 100 000 kr	3 040 000 kr	2 990 000 kr	2 410 000 kr	Timber truck: Löfroth and Svenson (2012). Other: Skogforsk (2011).
Depreciation, years	7	7	5	5	Timber truck: Löfroth and Svenson (2012). Other: Skogforsk (2011).
Interest rate	6.5%	6.5%	6.5%	6.5%	
Salvage value, kr	315 000 kr	456 000 kr	448 000 kr	361 000 kr	Skogforsk (2011).
Tax, year	44 000 kr	42 000 kr	42 000 kr	44 000 kr	Skogforsk (2011).
Insurance, year	63 000 kr	44 100 kr	68 200 kr	63 000 kr	Timber truck: Löfroth and Svenson (2012). Other: Skogforsk (2011).
Other fixed costs	33 600 kr	41 400 kr	29 900 kr	29 900 kr	Timber truck: Löfroth and Svenson (2012). Other: Skogforsk (2011).
Use per year, hours	3 200	3 200	3 200	3 200	Skogforsk (2011).
Annual fixed costs	*474 088 kr*	*610 263 kr*	*760 235 kr*	*636 758 kr*	
Variable costs					
Fuel cost, kr / litre	10.65 kr	10.65 kr	10.65 kr	10.65 kr	SPBI (2014).
Diesel consumption, driving, litre/km	0.47	0.52	0.54	n/a	Skogforsk (2011).
Diesel consumption, loading, litre/hours	7	7	7	n/a	Skogforsk (2011).
Diesel consumption, unloading, litre/hours	7	4	7	n/a	Skogforsk (2011).
Average fuel consumption divided per driven km	0.55	0.57	0.61	0.42	Timber truck: Löfroth and Svenson (2012). Other: Skogforsk (2011). Based on typical transport setup.
Share of time spent driving	56%	61%	54%	68%	Timber truck: Löfroth and Svenson (2012). Other: Skogforsk (2011). Based on typical transport setup.

Share of time spent loading	31%	19%	24%	12%	Timber truck: Löfroth and Svenson (2012). Other: Skogforsk (2011). Based on typical transport setup.
Share of time spent unloading	5%	9%	14%	12%	Timber truck: Löfroth and Svenson (2012). Other: Skogforsk (2011). Based on typical transport setup.
Share of time spent waiting	8%	11%	8%	7%	Timber truck: Löfroth and Svenson (2012). Other: Skogforsk (2011). Based on typical transport setup.
Maintenance and other costs, kr/km	1.53 kr	1.37 kr	1.49 kr	1.98 kr	Timber truck: Löfroth and Svenson (2012). Other: Skogforsk (2011).
Average speed, km/h	60	60	60	60	
Loading capacity, m^3	120	140	128	114	
Loading capacity, tonnes	34.9	39	37	40	Biofuel payload considering weight of truck and containers. Truck gross weight in Sweden is 60 tonnes.
CO_2 emission kg/litre diesel	2.67	2.67	2.67	2.67	EPA (2005).
CO_2 emission per km	1.474	1.511	1.627	1.121	
Cost per km	*7.41 kr*	*7.39 kr*	*7.98 kr*	*6.45 kr*	

Staff costs

	Costs	**Source / Comments**
Annual salary	310 375 kr	Sveriges åkeriföretag (2013). (Labour union collective agreement for driver with more than 4 years' experience including holiday pay)
Working hours per year	1 800	Löfroth and Svenson (2012).
Supplement for inconvenient working hours, per hour	27.36 kr	Sveriges åkeriföretag (2013). (Labour union collective agreement for work between 6 p.m. and 6 a.m.)
Share of inconvenient working hours	50%	Skogforsk (2011). (For typical setup).
Taxes	31.42%	Skatteverket (2014).
Collective insurances, pension, etc.%	7.06%	Based on agreements with the union. The amount may vary depending on the employer and union and increases with a higher salary.
Over-head costs, per working hour	43 kr	Löfroth and Svenson (2012).
Annual cost	*541 306 kr*	

Table 7. Rail engine

	RD-engine	**Modern engine**	**Used RC4**	**Source / Comments**
Fixed costs				
Purchase price	22 000 000 kr	36 750 000 kr	10 000 000 kr	Rd: Green Cargo (2012b). Other: Nelldal (2011).
Depreciation, years	20	25	10	Nelldal (2011).
Interest rate	6.5%	6.5%	6.5%	
Overhead costs	18%	18%	18%	Nelldal (2011).
Train speed km/h	70	70	70	
Annual fixed costs	*2 141 700 kr*	*3 143 963 kr*	*1 563 500 kr*	

Fixed costs are allocated based on utilization. However, it would be difficult to find full utilization of the engine outside the biofuel system due to difficulties in finding suitable assignments during weekends and summers where the biofuel system do not run, as these are periods with less demand for freight transport. The biofuel system is, therefore, allocated 50% of the fixed costs for weeks outside the system. For the base scenario this equals 75% of the fixed costs. As a comparison, the base scenario constitutes 85% of the average annual km for an electric freight rail engine in Sweden (106 000 km (Trafikanalys, 2014), although these statistics also include engines with unusually low usage such as backup engines and engines under repair).

Variable costs				
Weight, tonnes	78	83	78	
Electricity consumption, kWh per enginekm	5	5	5	Nelldal (2011).
Price per kWh electricity	0.6183	0.5737	0.6183	Trafikverket (2014). (Price list for rail including loss surcharge based on engine type).
CO2 emission kg/kWh	0.02	0.02	0.02	Brander, et al. (2011), Svensk Energi (2014). (Swedish electricity mix).
Maintenance costs per km	7.00 kr	6.30 kr	7.88 kr	Nelldal (2011).
Train path charge, per train km	3.40 kr	3.40 kr	3.40 kr	Trafikverket (2014). (Assuming a mix between high, medium, and low charge lines).
Track charge, per gross tonne km	0.005 kr	0.005 kr	0.005 kr	Trafikverket (2014).
Overhead costs	18%	18%	18%	Nelldal (2011).

Staff costs

	Line-haul driver	**Shunting operator**	**Source / Comments**
Annual salary	373 564 kr	323 483 kr	Green Cargo (2013). (Rail operator Green Cargo salary for driver class F10 and shunting operator including holiday pay).
Working hours per year	1 600	1 600	Green Cargo (2012a). (Can vary depending on the share of night work, number of holidays worked etc.).
Supplement for inconvenient working hours, per hour	40.57 kr	40.57 kr	Green Cargo (2013). (For work between 7 p.m. and 6 a.m.).
Share of inconvenient working hours	50%	50%	Estimate based on current setup.
Other surcharges and supplements, %	5%	5%	On-call time, allowances during travel, overtime pay etc. and other added supplements to the salary. Included as a general percentage as the exact amount will depend on the specific schedule for the driver.
Taxes	31.42%	31.42%	Skatteverket (2014).
Collective insurances, pension, etc.%	7.5%	7.5%	Based on agreements with the union. The amount may vary depending on the employer and union and increases with a higher salary.
Overnight allowance	30 000 kr		Estimate depending on individual scheduling.
Overhead costs	18%	18%	Nelldal (2011).
Annual salary costs	731 589 kr	609 989 kr	
Share of work time operating a train	66%	80%	Estimate based on discussion with rail operator for current setup.
Cost per train hour	*693 kr*	*477 kr*	

Table 8. Wagon

	used lgns	**new sgns**	**Source / Comments**
Fixed costs			
Purchase price	105 000 kr	735 000 kr	Nelldal (2011).
Depreciation, years	10	25	Nelldal (2011).
Interest rate	6.5%	6.5%	
Overhead costs	18%	18%	Nelldal (2011).
Annual fixed costs	*16 417 kr*	*62 879 kr*	Hourly cost calculated for each scenario based on utilisation. Wagons are assumed dedicated to the scenarios according to interview with rail operator.

Variable costs			Variable costs calculated for each scenario based on loaded fuel weight and allowed axle load.
Tara weight, tonnes	10	20	Green Cargo (2014).
Maximum load capacity, tonnes	35	70	Including container tara.
Load units per wagon	2	3	
Wagons per train	30	20	
Reserve wagons	10%	10%	Extra wagons in the system to use during repair, maintenance etc. Estimate from rail operator.
Maintenance costs per km	0.11 kr	0.16 kr	Nelldal (2011).
Track charge, per gross tonne km	0.005 kr	0.005 kr	Trafikverket (2014).
Electricity consumption kwh per grosstonkm	0.0155 kr	0.0155 kr	Nelldal (2011).
Overhead costs	18%	18%	Nelldal (2011).

Table 9. Load unit

	40m³	**Rotary**	**Source / Comments**
Purchase price	60 000 kr	69 000 kr	40m³: Interview with container manufacturer. Rotary: Estimated based on increased steel used compared to 40m³. The rotary containers currently used are not sold but are rented by the manufacturer as a part of a logistics concept at a confidential price. Cost estimates have been made based on the increased use of steel compared to the smaller 40m3 container.
Depreciation, years	7	7	Interview with container manufacturer.
Interest rate	6.5%	6.5%	
Tara weight, tonnes	2	2.85	
Maintenance costs	1 000 kr	1 000 kr	Interview with container manufacturer. (Average cost. Can vary substantially for individual containers depending on accidents etc. If nothing happens to the container, the maintenance cost is close to 0.).
Reserve load units	20%	20%	Extra load units in the system to use during repair, maintenance etc.
Annual costs	*11 521 kr*	*13 100 kr*	Per load unit, excluding reserve units.

Table 10. Terminal trucks

	Heavy rotary truck	**Light truck for 40m³ container**	**Source / Comments**
Fixed costs			
Purchase price, truck	4 210 000 kr	1 460 000 kr	Heavy truck: Skogforsk (2011). Light truck: Nelldal, et al. (2005).
Purchase price, rotator	600 000 kr		Interview with manufacturer.
Depreciation, years	7	10	Heavy truck: Skogforsk (2011). Light truck: Nelldal, et al. (2005).
Interest rate	6.50%	6.50%	
Salvage value, kr	720 000 kr	220 000 kr	Skogforsk (2011).
Annual fixed costs	*764 011 kr*	*178 600 kr*	Hourly cost calculated for each scenario based on utilisation. Trucks are assumed stationary at the plant/terminal.
Variable costs			
Fuel cost, kr / litre	10.65 kr	10.65 kr	SPBI, 2014.
Diesel consumption, litre per hour	15	13	Heavy truck: Skogforsk (2011). Light truck: Nelldal, et al. (2005).
Maintenance cost, truck per hour	47.00 kr	47.00 kr	Nelldal, et al. (2005).
Maintenance cost, rotor per hour	5.00 kr		Interview with manufacturer.
CO_2 emission kg/litre diesel	2.67	2.67	EPA (2005).
CO_2 emission per hour, kg	40.05	34.71	
Variable cost per hour	*212 kr*	*185 kr*	
Start-up cost per arriving train	2 500 kr	2 500 kr	
Unloading time per train, hours	4	7.7	Interview with industry (7 minutes per 40m³ container) and Enström and Winberg (2009).
Wood chip container truck (Hooklift)			
Fixed cost per hour		148 kr	See road cost calculations.
Salary cost per hour		301 kr	See road cost calculations.
Diesel consumption, loading/unloading, litre/hours		7	Skogforsk (2011).
Maintenance cost, etc., per hour		50.40 kr	Hard to estimate due to special operations with many start, stop, loadings, etc. Cost based on annual maintenance costs and hours in operation.
CO_2 emission per hour, kg		18.69	
Cost per hour		*574 kr*	Assumed hired on the open market by the hour as there are many independent road hauliers available.

Staff costs

	Costs	**Source / Comments**
Annual salary	356 628 kr	SCB (2014). (Average salary including holiday pay).
Working hours per year	1 800	
Supplement for inconvenient working hours, per hour	24.00 kr	Skogforsk (2011).
Share of inconvenient working hours	50%	Skogforsk (2011). (For typical setup).
Taxes	31.42%	Skatteverket (2014).
Collective insurances, pension etc.%	7.06%	Based on agreements with the union. The amount may vary depending on the employer and union and increases with a higher salary.
Annual cost	*523 770 kr*	
Hourly cost	291 kr	Assumed that staff is given other tasks when not receiving trains.

Table 11. Forest terminal

	Costs	**Source / Comments**
Fixed cost per MWh	4 kr	
Terminal receiving and sending by road		
Variable costs per MWh	10 kr	One stacking and one loading by wheel loader.
Terminal receiving by road and sending by rail		
Variable costs per MWh	15 kr	One stacking, one transport and one loading by wheel loader.
Terminal receiving by rail and sending by road		
Variable costs per MWh	17 kr	One unloading with rotary container truck, one stacking and one loading by wheel loader. Rotary container truck cost based on the previously presented cost calculation.
Wheel loader		
Diesel consumption per hour, litre	16	Skogforsk (2011).
CO_2 emission kg/litre diesel	2.67	EPA (2005).
Per stacking/transport, litre per MWh	0.035	Skogforsk (2011). (Based on 100 tonnes dry weight / hour).
Per loading, litre per MWh	0.046	Skogforsk (2011). (Based on 75.9 tonnes dry weight / hour).

Confidential terminal costs have been received from several terminals and the costs varied significantly. The most expensive terminal hade more than double the costs of the cheapest terminal. The reason for the large variations is that biofuel terminals often are co-located with old written-off round wood terminals with the same owner as the biofuel company. The round wood then carries the main terminal costs and biofuel is viewed as a marginal product, sometimes only charged its own operational costs. Staff, equipment etc. might also be shared between the terminals. The costs represent a likely average cost based on approximate cost for each operation supplied by the terminal operators.

Table 12. Shunting

	Used T44 diesel	**Rd line haul engine for shunting**	**Source / Comments**
Fixed costs			
Purchase price	10 000 000 kr	See previous calculation	
Depreciation, years	15		Nelldal (2011).
Interest rate	6.5%		
Overhead costs	18%		Nelldal (2011).
Utilisation, hours per year	2 500		Nelldal (2011).
Annual fixed costs	*1 170 167 kr*		T44 assumed to have other uses outside the biofuel system.
Variable costs			
Maintenance costs per hour	130 kr		Nelldal (2011).
Overhead costs	18%		Nelldal (2011).
Diesel consumption, litre per hour	37		Bäckström, et al. (2009). (For shunting).
Electricity consumption, kwh per hour		369	Based on energy consumption for diesel shunting.
Fuel cost, kr / litre	6.02 kr		SPBI (2014). (Rail traffic does not pay fuel taxes in Sweden.).
Price per kWh electricity		0.6183	Trafikverket (2014).
CO_2 emission kg/litre diesel	2.67		EPA (2005).
CO_2 emission kg/kWh		0.02	Brander, et al. (2011), Svensk Energi (2014). (Swedish electricity mix).
Number of shuntings	2	2	One in and one out from the terminal.
Engine hour per shunting	1h 30 minutes	1h	30 minutes in, 30 minutes out and 30 transport/set-up. No transport for Rd
Shunting staff per shunting, hours	2 h	1h 30 minutes	60 minutes shunting, 30 minutes administration and 30 minutes transport/set-up. No transport for Rd.
Line haul driver per shunting, hours	30 minutes	1h 30 minutes	T44: break test. RD: also shunting.

Table 13. Conventional intermodal terminal

	Costs	**Source / Comments**
Cost per container	182 kr	Sommar (2010). (Cost for medium size conventional terminal, 50 000 lifts per year excluding shunting).
CO_2 emission per container, kg	6.16	Bäckström, et al. (2009).

Table 14. Chipping

	Mobile terminal chipper	**Stationary electric chipper**	**Mobile roadside chipper**	**Source / Comments**
Costs for logging residues per MWh	23 kr	7 kr	40 kr	Workshop with industry representatives. (Logging residues has a higher wear one the equipment than round wood).
Cost for round wood per MWh	20 kr	5 kr	35 kr	Workshop with industry representatives.
Diesel consumption per MWh chipped, litre	0.35		0.48	At terminal: Eliasson, et al. (2012). Roadside: Lombardini, et al. (2013) Eliasson, et al. (2013).
Electric consumption per MWh chipped, litre		0.07		Skogforsk (2011).
CO_2 emission kg/litre diesel	2.67		2.67	EPA (2005).
CO_2 emission kg/MWh electricity		0.02		Brander, et al. (2011), Svensk Energi (2014). (Swedish electricity mix).

Table 15. Biofuel densities and capacities

	Bark	**Log chips**	**Logging residue chips**	**Saw residue chips**	**Sawdust**	**Stump chips**	**Whole three chips**	**Wood residue chips**	**Log**	**Logging residues**	**Source / Comments**
Density kg/loose m^3	350	271	295	300	300	288	300	225	367	173	WeCalc by Larsson and Nylinder (2014) COFORD (2003). Logging residues by Näslund (2006). Swedish conditions.
Energy MWh/m^3	0.65	0.79	0.78	0.65	0.58	0.77	0.8	0.8	1.07	0.38	WeCalc by Larsson and Nylinder (2014) COFORD (2003). Logging residues by Näslund (2006). Swedish conditions.
Moisture content in fuel can vary where newly harvested fuel with higher moisture content is heavier.											
Wagon type sgns											
Rotary container, per container											Calculation considerations allow for weight and volume on the rail car and fuel density.
Capacity, tonnes	15.75	12.2	13.3	13.5	13.5	13.0	13.5	10.1			Excluding container tara. Maximum weight is 20.15 tonnes.
Capacity, m^3	45	45	45	45	45	45	45	45			Volume is a limiting factor on all fuels.
Capacity, MWh	29.3	35.6	35.1	29.3	25.9	34.5	36.0	36.0			The containers are full by volume before the maximum allowed weight on the rail wagon is reached.
40m^3 container, per container											
Capacity, tonnes	14.0	10.8	11.8	12.0	12.0	11.5	12.0	9.0			Excluding container tara. Maximum weight is 21 tonnes.
Capacity, m^3	40	40	40	40	40	40	40	40			Volume is a limiting factor on all fuels.
Capacity, MWh	26	31.6	31.16	26	23	30.64	32	32			
Wagon type lgns											
Rotary container, per container											
Capacity, tonnes	14.7	12.2	13.3	13.5	13.5	13.0	13.5	10.1			Excluding container tara. Maximum weight is 14.7 tonnes.
Capacity, m^3	42.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0			Volume is a limiting factor on all fuels except bark, where weight is limiting.
Capacity, MWh	27.2	35.6	35.1	29.3	25.9	34.5	36.0	36.0			

Wood chip container truck											
Capacity, tonnes	37.0	32.5	35.4	36.0	36.0	34.6	36.0	27.0			Excluding container tara. Maximum weight is 37 tonnes and volume is 120 m^3.
Capacity, m^3	105.70	120.00	120.00	120.00	120.00	120.00	120.00	120.00			Volume is a limiting factor on all fuels except bark, where weight is limiting.
Capacity, MWh	68.7	94.8	93.5	78.0	69.0	91.9	96.0	96.0			
Wood chip truck											
Capacity, tonnes	39.0	37.9	39	39.0	39.0	39.0	39.0	31.5			Excluding container tara. Maximum weight is 39 tonnes and volume is 140 m^3.
Capacity, m^3	111.4	140.0	132.2	130.0	129.9	135.5	130.0	140.0			Weight is a limiting factor on all fuels except wood reside chips and log chips where volume is limiting
Capacity, MWh	72.4	110.6	103	84.5	74.7	103.8	104	112			
Timber truck											
Capacity, tonnes									40.0		
Capacity, m^3											
Capacity, MWh									116		
Forest residue truck											
Capacity, tonnes										22.1	
Capacity, m^3										128	
Capacity, MWh										49.1	

The author is happy to answer any further questions via e-mail regarding the cost calculations and data used.