



# Solid biomass fuel terminal concepts and a cost analysis of a satellite terminal concept

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## Preface

This report collects the research findings of subtask 2.2.4.2 in BEST-programme phase 1 executed during 2013–2014. The key topic has been the outlining and designing of new biomass fuel terminal concepts. The background on this study lies in the previous terminal research executed at VTT Technical Research Centre of Finland Ltd by Impola and Tiihonen (2011).

Three concepts of solid biomass fuel processing terminals (feed-in terminal, fuel upgrading terminal and satellite terminal) are described in this report. The most common terminal type, a transshipment terminal is also described. This report also includes the results of a cost analysis executed for a satellite terminal concept.

The presented terminal concepts take into account different sources of forest biomasses (uncommercial stem wood, delimbed stem, whole tree, stumps and logging residues) delivered by several suppliers, the processing of the raw materials to fuel chips or hog fuel, and the delivery of the fuels to customers reliably and flexibly around the year.

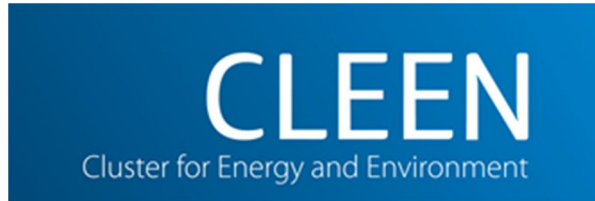
The new terminal concepts will help the whole logistics chain by evening the fluctuations in biomass demand and production. The presented professional fuel handling and processing methods facilitate high fuel quality and reasonable supply costs of delivered fuel. This goal can only be reached through efficient terminal operations and efficient use of infrastructure and machinery throughout the year around the whole supply chain.

This study was funded by VTT and Tekes through the BEST programme. Ville Hankalin and Jaakko Nummelin (ÅF Consult) were responsible for writing the biomass drying section of the report. Miska Kari from Mantsinen Oy provided valuable data on terminal biomass and handling processes, and provided valuable guidelines for outlining the terminal concept.

New biomass processing and storage methods and automation development as well as further terminal business concepts will be studied in phase 2 of the BEST programme during the years 2015–2016.



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## Abstract

As forest fuel demand increases, new logistical solutions are needed. Most of the increase in use is expected to take place in large heat and power (CHP) production units which set special requirements for the supply as both procurement volumes and transport distances increase. Biomass fuel terminals broaden the spectrum of available supply options by offering cost-effective large-scale biomass storage and processing options for securing the fuel supply in all conditions.

This report presents three Nordic developing solid biomass fuel terminal concepts: a satellite terminal, a feed-in terminal and a fuel upgrading terminal. The most common current terminal concept, a transshipment terminal, is presented for comparison. There are several transshipment terminals (forest fuel storage and manufacturing sites) in operation in Finland, as almost every forest fuel procurement company stores some of its supplied wood fuel in storage sites with good connections to long-distance transport routes.

Examples of feed-in terminals (forest fuel storage and manufacturing site near user sites) can be found for example in terminals owned by energy companies Söderenergi AB (Södertälje, Sweden), Jyväskylän Energia and Rovaniemen Energia. Large scale satellite terminal operations (large centralized forest fuel storage and manufacturing site located remotely from user/users) are being run, for example, in Stockarydsterminal in Sävsjö, Sweden. Fuel upgrading in terminals has so far had a rather marginal role, except for the natural drying of raw forest fuel material during terminal storage.

This report presents the key terminal activities, terminal line-ups as flow charts, terminal area requirements based on terminal output and storage rotations. In addition to this, the report presents a detailed cost analysis on the fuel production costs in the satellite terminal concept with different terminal outputs (0.1, 0.3, 0.7 and 1 TWh) for different raw fuel materials (uncommercial stem wood, delimbed stem, whole tree, stumps and logging residues).

The cost calculation was executed by analyzing material fed to comminution (chipping or crushing) directly from a transport unit (a biomass truck or a train), or feeding

of material that has been stored in a terminal and is later comminuted. The storage period increased the costs of produced fuel (by 22% to 78%) due to costs incurred by the additional load-unload sequences, and terminal transport from storage to comminution and costs of capital tied to storages.

The largest analyzed terminal size class was based on 1 TWh (500 000 solid-m<sup>3</sup>/year), which was found to have the lowest terminal handling and processing costs. For comminution, a stationary chipper and a mobile crusher were studied. A stationary chipper was found to be the more economical machine for terminal comminution, and the comminution cost with a stationary chipper was 10–13% lower compared to a mobile crusher. However, a stationary chipper is not suitable for all forest fuel materials like stumps, and from an economic perspective a stationary machine is not fit for the smallest studied terminals (0.1 and 0.3 terminals) so a mobile crusher was selected as the comminution machine for a cost comparison between all studied terminal outputs and forest fuel materials.

The fuel produced in terminals with the lowest terminal costs was forest chips made from logging residues. The cost for logging residue chips with all operational and fixed terminal costs included, fed from a biomass truck and loaded to the transport vehicle as chips was 2.37 €/MWh. In the smallest transshipment type terminal (0.1 TWh) the equivalent terminal costs were 3.31€/MWh due to the higher comminution costs and higher fixed costs in a smaller terminal. For delimbed stems the respective costs were almost equal, 2.33 €/MWh (1 TWh terminal, chipped, direct feed to comminution) and 3.32 €/MWh (0.1 TWh terminal, crushed, direct feed to crusher).

The satellite terminal cost analysis reveals that a large scale terminal can be a cost efficient solution to an overly provincial forest biomass procurement challenge. If it is assumed that the cost for delimbed stems delivered to a terminal (loaded in a transport vehicle) is 13 €/MWh (standing price + harvesting + transport) and the fuel delivery from a terminal costs 6/MWh (train, 600km), the total cost for fuel delivered from, for example, the Kainuu region to the Finnish metropolitan area is 21.9 €/MWh to 22.4 €/MWh (delimbed stem, 1 TWh, crushing, direct feed 2.6 €/MWh or delimbed stem, through storage, crushed 3.4 €/MWh). This cost at plant is 5–9% higher than the price paid for forest chips in Finland on average in June 2014 (Bioenergia-lehti 04/2014). It must be noted that the example above refers to a supply situation where wood fuel is transported 600km by railway, whereas the common supply distance for direct supply chains is 80–120km.

The figures indicate that terminals do not create direct cost benefits per se: direct supply chains are more economical compared to supply through terminals. However, there are several indirect benefits that can be reached via fuel supply through terminals: regional fuel procurement can be widened to a national scale, security of supply increases (easily available storages), large supply volumes can be delivered by an individual operator, prices remain more stable and a more even quality of delivered fuel can be achieved.

## Tiivistelmä

Kiinteiden biopolttoaineiden ja etenkin metsähakkeen kysynnän kasvaessa tarvitaan uusia logistisia ratkaisuja. Metsäpolttoaineiden käytön on esitetty kasvavan etenkin suurissa lämmön ja sähkön yhteistuotantokohteissa (CHP), jotka asettavat polttoainehankinnalle erityishaasteita polttoaineen hankintamäärien kasvaessa pistemäisesti ja kuljetusmatkojen pidentyessä. Biomassaterminaalit laajentavat käytettävissä olevia logistisia mahdollisuuksia tarjoamalla tehokkaita biomassan varastointi- ja käsittelymahdollisuuksia, joilla polttoaineen saatavuus voidaan varmistaa kaikissa olosuhteissa.

Tämä raportti esittelee kolme pohjoismaista kehittyvää kiinteän biopolttoaineen terminaalikonseptia: satelliitti-, syöttö- ja polttoaineen jalostusterminaalin sekä vertailukohtana yleisimmän nykyisen terminaalityypin siirtokuormausterminaalin. Siirtokuormausterminaaleja (metsäpolttoaineen varastointi- ja valmistuspaikkoja) löytyy Suomesta useita liki jokaisen metsäenergiatoimijan varastoidessa energiapuuta keskitetysti hyvien kaukokuljetusreittien läheisyydessä. Syöttöterminaaleista (lähellä käyttöpaikkaa sijaitseva metsäpolttoaineen varastointi- ja valmistuspaikka) on löydettävissä esimerkkejä Suomesta esimerkiksi Jyväskylän energian ja Rovaniemen energian omistamista terminaaleista sekä Ruotsista Söderenergi AB:n omistamasta syöttöterminaalista Södertäljessä. Laajamittaista satelliittiterminaalitoimintaa (suuri keskitetty metsäpolttoaineen varastointi- ja valmistuspaikka etäällä käyttäjistä/käyttäjistä) harjoitetaan esimerkiksi Ruotsissa Sävsjön kunnassa Stockarydsterminalenissa. Polttoaineen jalostustoiminta terminaaleissa on toistaiseksi ollut vähäistä varastoinnin aikaista luonnonkuivausta lukuun ottamatta.

Raportti esittelee terminaalien tärkeimmät tehtävät, terminaalikokoonpanot kaaviokuvina, terminaalien pinta-alatarpeen varastokoon ja läpivirtauksen mukaan. Tämän lisäksi raportti esittää yksityiskohtaisen laskelman satelliittiterminaalissa tuotettavan polttoaineen tuotantokustannusten muodostumisesta eri terminaalikokoluokissa (0,1, 0,3, 0,7 ja 1 TWh) sekä eri polttoaineen raaka-aineille (järeä eikaupallinen runkopuu, energiaranka, kokopuu, kannot ja hakkuutähde).

Kustannuslaskelma toteutettiin tarkastelemalla suoraan ajoneuvosta terminaalimurskaukseen tai -haketuksen ohjautuvaa polttoaineen raaka-ainetta sekä terminaali-



kentällä varastoitua ja varastoinnin jälkeen hienonnettavaa metsäpolttoaineen raaka-ainetta. Varastointi lisäsi polttoaineen tuotantokustannuksia huomattavasti lisääntyneistä käsittely- ja kuljetustoimenpiteistä sekä varastoihin sitoutuneen pääoman kustannuksista johtuen.

Suurin tarkasteltu terminaalikokoluokka oli 1 TWh (500 000 k-m<sup>3</sup>/vuosi), joka osoitautui myös terminaalikustannuksiltaan edullisimmaksi. Kiinteä hakkuri osoittautui edullisimmaksi polttoaineen hienonnutmenetelmäksi, ja hakkurin kustannus oli 10–13 % mobiilimurskainta alhaisempi. Kiinteä hakkuri, kuten hakkurit yleensäkin, ei sovellu kaikille metsäpolttoaineen raaka-aineille (kannot) eikä pienimpiin terminaalikokoluokkiin (0,3 ja 0,1 TWh), joten kokonaistarkastelussa kaikkia terminaalikokoluokkia vertailtaessa hienonnutkoneena oli vaakasyöttöinen mobiilimurskain.

Edullisin terminaalissa tuotettu polttoaine oli hakkuutähdehake, jonka terminaalikustannus suoraan biomassarekasta hakkuriin syötettynä, haketettuna ja kaukokuljetusvälineeseen lastattuna kaikki terminaalin kiinteät kustannukset huomioiden oli 2,37 €/MWh. Pienimmässä siirtokuormaustyyppisessä terminaalissa (0,1 TWh/a) vastaavan polttoaineen tuotantokustannus mobiilimurskaimella murskattuna oli 3,31 €/MWh pienen terminaalin korkeammista murskauskustannuksista sekä terminaalin korkeammista kiinteistä kustannuksista johtuen. Karsitulle rangalle vastaavat luvut ovat liki samat 2,33 €/MWh (1 TWh haketettu, suora syöttö hakkuriin) ja 3,32 €/MWh (0,1 TWh, murskattu, suora syöttö murskaimeen).

Satelliittiterminaalien kustannustarkastelu osoittaa, että uudella suurimittakaavaisella terminaalitoiminnalla voidaan vastata kustannustehokkaasti ylimatekunnalliseen metsäpolttoaineen hankintahaasteeseen. Jos oletetaan, että esimerkiksi karsittu ranka saadaan toimitettua terminaaliihin hintaan 13 €/MWh (kantohinta, korjuu ja kuljetus) ja toimitus terminaalista käyttöpaikalle maksaa 6 €/MWh (juna 600 km), on esimerkiksi Kainuusta pääkaupunkiseudulle toimitettavan metsäpolttoaineen hankintakustannus käyttöpaikalla 21,9–22,4 €/MWh (1 TWh, murskaus, suora syöttö, 2,7 €/MWh tai murskaus, varastoitu ranka 3,4 €/MWh). Tämä on noin 5–9 % Suomessa vuonna 2014 maksettua metsäpolttoaineen hintaa (20,7 €/MWh, Bioenergia-lehti 04/2014) korkeampi.

Suoraa kustannushyötyä ei esimerkin tapauksessa saavuteta: Suorat toimitusketjut ovat terminaalitoimitusketjuja edullisempia. Välillisiä hyötyjä on kuitenkin useita, kuten alueellisen hankinnan laajeneminen valtakunnalliseksi, toimitusvarmuus, suuri toimitusvolyymi, hintavakaus ja tasainen laatu. Merkittävää on, että suoriin toimitusketjuihin verrattuna tässä hankintaketjussa metsäpolttoaine kuljetetaan rautateitse yli 600 km etäisyydelle raaka-ainelähteestä, kun tavanomainen metsäpolttoaineen kuljetusmatka on 80–120 km.

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## 1. Introduction

A new record was made in the use of forest chips in heat and power production in Finland in 2013 as a total of 8 million solid cubic metres of forest chips was used. In addition to this 0.7 million solid cubic metres was used in domestic heating. In heat and power production small wood (delimbed stem, whole tree, pulp wood) accounted for 3.6 million solid cubic metres, logging residues 2.8, stump wood 1.2 and uncommercial stem wood 0.5 million solid cubic metres (Metla 2014). In energy units, the current use of forest chips in Finland in heat and power production corresponds to 16 terawatt hours (TWh).

Current forest fuel supply is divided between three major procurement methods: comminution at the roadside, comminution at a plant and terminal comminution. The share of terminal comminution is 12% for logging residues 21% for small wood, 36% for stump wood and 46% uncommercial stem wood (Metsätehon tulokalvosarja 4/2013).

According to the Finnish energy and climate strategy (TEM 2013) the goal of the use of forest chips in heat and power production by 2020 is 25 TWh which corresponds to 13 million solid cubic metres of wood. This poses the challenge of increasing the use of forest chips by nearly 5 million solid cubic meters. Additionally there are plans to increase the use of industrial timber (pulpwood) by over 4 million cubic meters in Central Finland (Laitinen 2014). This increase in wood felling will bring more logging residue and stumps to market, but as the new bio refinery installation focuses on pulpwood use, the market will tighten on pulp wood and possibly partly on small wood too.

This report combines the results on current wood and agro-biomass terminals (usually a transshipment terminal) and new identified terminal concepts that facilitate cost efficient wood fuel supply for answering to increased demand and more complex supply schemes over long transport distances. Based on actual existing examples of operating terminals, the report identifies three different developing terminal types (satellite terminal, feed-in terminal fuel and upgrading terminal) and presents a detailed cost analysis of a satellite terminal, a fuel production terminal located far from the users near abundant biomass resources that supplies fuel for different users.

It is obvious that additional handling and storage times add costs to supplied wood fuel compared to direct supply chains that are generally more cost efficient than terminal supply chains. However, the terminal chains have an important function when the fuel supply is studied in a broader context. The terminal offers security of supply for a fuel user: it can also even out fuel quality fluctuation and by utilising a terminal supply wood fuel harvesting season and utilization of production machinery heavily burdened by high investment costs can be distributed more evenly over the traditionally quieter seasons. Through this there is potential for indirect cost savings through more economical wood fuel harvesting for machine entrepreneurs.

It can be concluded that the value for security of supply and improved quality equals the cost generated from dry-matter losses, capital tied in storage and costs from additional loading-unloading sequences (i.e. terminal costs). These costs are partly offset by cost savings on more economical material handling in terminals, energy content increment during storage and more efficient logistical solutions in transportation.

As the biomass fuel demand grows with new cogeneration investment plans (e.g. Helen, Vuosaari, TSET Naantali,) and local fuel supply does not meet the growing user demands, supply over long transport distances becomes unavoidable. By centralizing the fuel production to large fuel production terminals, purpose-built heavy-duty machines can be utilized, lowering the production costs compared to traditional wood and agro-biomass supply. Large volumes mean high utilization rates for machines and efficient handling of different material resulting in low unit costs. It is also worth noting that in the low demand areas the price of energy wood is lower compared to high-demand areas.

Currently the most significant bottleneck for long-haul supply of wood and agro-biomass is the lack of suitable railway transport options. In an optimal solution, when supplying fuel from a distant satellite terminal, the fuel would be loaded to a train in the terminal and transported directly to a user site.

## 2. Current forest fuel supply

### 2.1 State of the art – most common forest fuel supply chains

Descriptions of different forest fuel supply chains are well documented in recent publications. The following classification is based on the article “Forest energy procurement: state of the art in Finland and Sweden” (Routa et al. 2013). The presented shares of production amounts for different supply chains are based on the most recent results of Metsäteho (Metsätehon tuloskalvosarja 4/2013).

Forest energy supply chains are built around the comminution phase. The position of the chipper or crusher in the procurement chain determines the state of biomass during transportation and whether subsequent machines are dependent on each other, that is, *whether the system is hot or cool*. In a “hot system” subsequent machines are dependent on each other. In a “cool system” the machines involved operate independently of each other which eliminates a time delay between machines. Comminution may take place on the logging site, at the roadside landing, at a terminal, or at the plant. By concentrating the comminution to terminals or plants it is possible to work effectively and get rid of the problems of “hot systems” such as waiting and queuing at the landing. (Routa et al. 2013)

In general, forest energy supply chains can be divided into chains based on *Roadside comminution* (Figure 1), *Terminal comminution* (Figure 2) or *Comminution at the plant* (Figure 3).

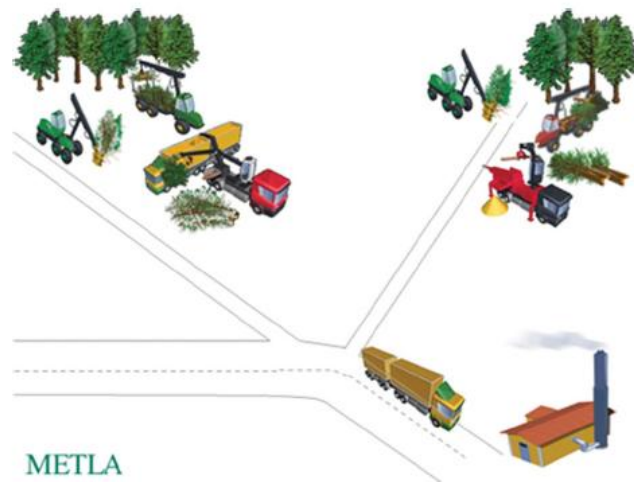


Figure 1. Forest fuel supply chain based on comminution at the landing. On the left, logging residues from final harvest, truck-mounted chipper. On the right, small diameter trees from early thinning, truck-mounted chipper. (Figure: Metla)

### 2.1.1 Roadside comminution

*Roadside comminution* is the predominant option of forest chip production. In Finland, about 75% of the logging residues are comminuted at the roadside landing close to the logging site. In Finland in 2010, about 70% of the small-sized wood and 29% of the large-sized uncommercial round wood for energy was comminuted at roadside. The biomass is forwarded to the landing and piled there. Comminution is performed at the landing using farm tractor-driven chippers in smaller operations and heavy truck-mounted chippers or crushers in large-scale Finnish operations. Chips are blown directly into a chip truck with 100–140 m<sup>3</sup> bulk load space, a process that makes the system “hot” and vulnerable, that is, subsequent machines are dependent on each other. Chippers or chip trucks may waste a remarkable amount of time by waiting and for other stoppages, consequently reducing their operational efficiency. Furthermore, large biomass storage piles and the space requirements of chipper and chip trucks bring large space requirements.

Roadside comminution is a flexible and well proven production chain. The availability of harvesting machinery in the Nordic countries is very good. With a separate chipper and chip truck, the chain becomes hot and the utilization rate of chipper may be low with long waiting times, leading to low operational efficiency. The roadside storage space has to be large, and in practice the storage areas are often too small and muddy. (Routa et al. 2013)



Figure 2. Forest fuel supply chain based on comminution at the terminal. (Figure: Metla)

### 2.1.2 Terminal comminution

*Terminal comminution* means that the forest biomass is transported to the terminal for comminution, and then optionally stored, mixed, and transported by truck, train or barge to the plant. About 12% of logging residues, 21% of all the chips from small-sized wood and about 36% of stump and root wood were comminuted at terminals in Finland in 2012. About 46% of large-sized uncommercial round wood was comminuted at terminals (Metsätehon tulokset 4/2013).

Due to high land acquisition and land construction costs, terminals require large volume flows to be competitive and all the area of the terminal must be used efficiently. Terminal comminution chains diminish the interaction between comminution and transport and the quality monitoring and quality management possibilities of wood fuel supply are significantly higher compared to direct supply chains. Furthermore, by utilizing terminals the security of fuel deliveries can be guaranteed in all seasons. In addition the fuel production machinery can be directed to operate in terminals instead of roadside storage during the high demand season for reaching high production volumes. Terminals can also facilitate year round employment for the fuel procurement chains. During low demand season the fuel procurement chain can be employed to the procurement of fuel material from forests for filling up the terminal storage.

Today's comminution process (chipping/crushing) whether in the terminal or at the roadside is effective and can handle most types of biomass. A weakness in the terminal supply option is the low bulk density of the biomass in transportation to the terminal which often takes place in an unprocessed form as loose residues,



whole trees or pieces of stump wood. In the current biomass terminals additional transport distances (compared to direct supply chains), high terminal area investment costs and limited value added to the chain are weaknesses of the terminal comminution system.

In Finland, the size of the load is usually limited by the bulk volume rather than legal mass capacity. In terminal supply chains comminution and long-distance transportation are independent of each other, which results in a high degree of capacity utilization and thus relatively low comminution costs. Loading of chip trucks with a wheel loader, however, has interactions with the chip transportation. In addition, extensive investment in the centralized comminution system presupposes full employment and large annual comminution volumes. Identifying ideal terminal areas is challenging and the total costs of the supply chain can be relatively high. (Routa et al. 2013)



Figure 3. Forest fuel supply chain based on comminution at a power plant. (Figure: Metla)

### 2.1.3 Comminution at plant

*Comminution at plant* makes the chipper and chip truck independent of each other. About 13% of the logging residues, about 9% of all the chips from small-sized wood and about 43% of stump and root wood were comminuted at power plants in Finland in 2012 (Metsätehon tulostusraportti 4/2013). In addition, in 2009, 25% of the large-sized uncommercial round wood for energy was comminuted at power plants (Metsätehon tulostusraportti 4/2013). By shifting the comminution process from roadside to plant, the technical and operative availability of the equipment increases, control of the procurement process improves, demand for labour de-

creases, and the control of fuel quality improves. Heavy stationary equipment may be used: chippers or crushers, which are suitable for the comminution of all kinds of biomass, including stumps and recycled wood. In general, fuel flow should be as high as possible in order to ensure the largest benefits. Because the investment cost is high, only large plants can afford a stationary crusher. The system can reduce interactions between transport and comminution. To be economical, the supply must be large-scale and produce more than 100 000 m<sup>3</sup> annually. If the transportation distances are short, comminution at plant is the most cost-efficient supply chain. The weakness of this system, if the material is not compact, through, for example, bundling or precomminuting, is low bulk density, leading to high transport costs. (Routa et al. 2013)

### **3. Terminal supply chains**

A biofuel terminal is a part of the logistical chain from a forest stand to usage site. The following terminal functions can be distinguished: raw material storage, storage for ready-made fuel, and fuel production site. In addition to these, depending on the distance from the terminal to the usage site, short-haul or long-haul terminals can be identified.

Terminals can also be named after their main activity, for example, feed-in terminal (short haul, near plant, supplying fuel to the plant according to current demand), satellite terminal (long haul, large fuel production terminal located far from usage site, near abundant fuel resources, producing fuel for distant user/users). The most common terminal type today is a transshipment terminal, a rather small fuel material storage and fuel manufacturing site which is emptied by supplying wood fuel during the high fuel demand season.

The term satellite terminal has previously been introduced in a report “Kainuun biomassaterminaaliverkostohankkeen toteutettavuus selvitys” (Pöyry 2009). Karttunen et al. also mention satellite terminals in their paper “Cost-efficiency of intermodal container supply chain for forest chips” (Karttunen et al. 2013). However, specific descriptions of the satellite terminal concept are not available.

This report presents the transshipment terminal as the prevailing current terminal concept. Satellite terminals, feed-in terminals and fuel upgrading terminals are regarded as new developing terminal concepts. Examples of all presented developing terminals exist in Sweden and Finland and the presented descriptions are based on actual operational terminals.

#### **3.1 Current terminal supply chains**

##### **3.1.1 Transshipment terminal**

Most of the terminals currently operating in Finland can be described as transshipment terminals. The annual average fuel flow is usually between 0.1 TWh/year

and 0.3 TWh/year, which equals to 50 000–150 000 solid m<sup>3</sup>/year. In this scale the area requirement of a transshipment terminal is around 3 hectares of preferably asphalted area.

The activities of transshipment terminals consist of periodical storage and fuel production. Raw fuel material is transported to the terminal site during the low season in heating and later chipped/crushed and transported to usage sites during the high season. Normally only mobile machines are used and infrastructure is minimal – usually there is just an open area for fuel storage from which the material is comminuted directly to fuel trucks. All measurements are based on the loader scales of the operating machines. Because storage piles are built by timber trucks, a 5m pile height is common for transshipment terminals. Figure 4 presents the schematic parts of a transshipment terminal. The optimal operative principle is to comminute the material directly from the storage piles to chip trucks. In case intermediate chip storage is needed a wheel loader is used for the loading of chip trucks.

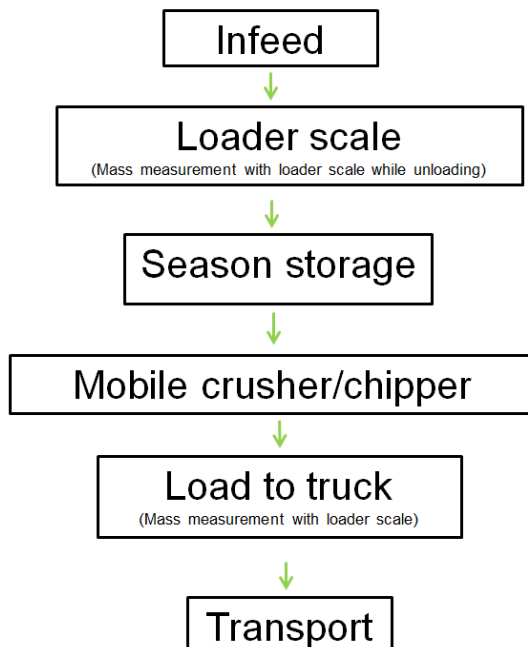


Figure 4. Chart layout of a transshipment terminal.

The raw fuel material is usually owned by a forest or an energy company. A single contractor or several separate contractors are responsible for fuel production and transport. They are hired on a contract basis and operate in a single terminal periodically as required by fuel user demands.

## **3.2 Terminal functions**

### **3.2.1 Raw material storage in a terminal**

A terminal can be a centralized storage site for the raw fuel materials delivered from the forest or from agriculture (stumps, logging residues, small diameter wood, large sized round wood, straw), from which the usually naturally dried (during the storage period) material is forwarded to the power plant for utilization or elsewhere to be crushed or chipped. This type of storage site is usually located in a logistical-ly optimal place, where the material can be easily be transported even during spring and autumn frost-heave seasons with limited forest road accessibility.

### **3.2.2 Storage for ready-made fuel in a terminal**

A terminal may also act as a storage site for ready-made fuel (chips, crushed material, sawmill industry side products and wood/agro-biomass blends), and as a buffer storage, securing fuel supply in all conditions and during all seasons to either one or for several plants. Today, this type of buffer storage is seen in the yards of most power plants with a sufficient amount of fuel for a weekend or for a longer period (Figure 4). The other type of ready-made fuel storage is a feed-in terminal located in the vicinity of the usage site. These types of terminals are especially beneficial in the cases where the fuel storage capacity at the usage site is limited.

The main motivation for utilizing fuel feed-in storage comes however from the fact that the direct supply chains are always not sufficiently secure for high utilization season or agile or enough to react to rapid changes in the wood fuel use, for example. On the other hand, storage space at power plants may be limited or the plant may get fewer direct deliveries from forest sites during weekends. In addition to this, extremely cold periods during winter and difficult road conditions during spring and autumn may also limit wood fuel deliveries and thus increase the need to utilize easily accessible terminal fuel storage.



Figure 5. Storage sites of ready-made fuel and raw fuel material established in the close vicinity of usage sites secure the plant's fuel supply in all conditions.

### **3.2.3 Fuel production in a terminal**

In addition to being used as storage sites of fuel or raw fuel material, terminals are increasingly being perceived as production facilities for forest and agro-fuels where different raw materials are chipped and crushed for providing ready-made fuels for different types of user facilities. The output of this type of terminal has been wood chips or crushed wood from small-sized stem wood, whole trees, stumps and logging residues. Part of the fuel terminal will also produce fuels from other smaller sources, for example, from agricultural residues and will develop new business models suitable for fuel terminals. The new business models could include: processing mulch for gardening, the production of materials for soil enrichment and processing recycled materials.

Depending on the size (output), location, business model and ownership structure of the terminal, its activities may be continuous or periodical. These factors also determine the equipment base (stationary or mobile) and sizing of the machinery. Terminals of the future are expected to be larger than today's due to potential savings in large scale terminal operations and increasing fuel demand by several large users. Bigger size (output) usually means continuous operation and more options for fuel handling and fuel quality improvement (pre-crushing/crushing, natural/artificial drying, sieving, blending).

### **3.2.4 Fuel handling and quality management**

The establishment of a terminal causes significant investment costs and compared to direct supply chains, the terminal chains cause at least one additional unloading-loading sequence. These costs can at least be partly offset by utilizing heavy-duty chippers and crushers developed specifically for terminal conditions. This machinery is usually electrically powered and consumes less energy per produced quantity of fuel (also the servicing of the machinery is simpler in the terminal). In addition to this, within the controlled terminal conditions the quality parameters of

fuels can be improved during controlled terminal storage creating an additional energy value increment offset for terminal costs. The improved energy density of produced fuel results in the lowering of transport costs, as well as full loads and efficient loading/unloading of the arriving and departing trucks. Additionally, since large volumes of fuel are delivered from the same producer the quality is more evenly based on well managed processes and long customerships, which helps to control the combustion process and thus improves the run ability of the power plants. Extraction of the impurities (pre-crushing), particle size management (sieving), fuel drying (usually natural drying, possibly also artificial) and production of desired fuel blends are well matched activities for biofuel terminals.

### **3.2.5 Terminal related logistics**

Logistical benefits can be obtained when the terminal is located near highway crossings or at junctions between transport modes (for example, truck–railway or truck–barge). Truck transport dominates current biofuel transport, however, there is a huge potential in the increase of railway transportation of ready-made fuels. As transport distances become longer, the economical benefit of railway transportation become more and more apparent. The terminals equipped with railroad connections will most likely be combined terminals for industrial round wood and wood and agro-biomass. Railway transportation of energy wood and industrial round wood are likely to be compounded. This poses a challenge for space requirements in the terminals as enough space and machinery must be allocated for efficient loading and unloading of the trains. Good examples of biomass railway transportation can be found in Sweden, where several railway operators provide railway logistics solutions for different biomass users. It is important to note that Sweden opened its railway freight market in 1996 (Andersson 2012). This development is yet to take place in Finland.

### **3.2.6 Hybrid terminal functions**

In addition to above-mentioned terminal functions and roles, a terminal can also act as a part of common industrial wood procurement or as a side business of, for example, recycled material processing. This kind of hybrid terminals are combinations of different material handling businesses that offer synergy benefits from one operation type to another.

## **3.3 Key terminal features**

### **3.3.1 Location of the terminal**

The geographical location of a terminal is determined by the business model of the terminal: in a case where the terminal is mainly used for producing fuel and feed-

ing a particular power plant, the terminal is usually located as near to the plant as possible (a feed-in terminal).

In a case where the terminal is operated by a fuel producer, the terminal location is defined by the regional availability of fuels, and on the other hand, the demand for the fuel. Thus, when optimizing the terminal location, both transport distances of the raw material to the terminal and delivery distances of ready-made fuel to the users must be considered.

### **3.3.2 Terminal site**

Biomass terminal sites have usually been established in old sand or gravel pits or other soil extraction sites, or other existing industrial sites that have been left without use. They usually are located outside residential areas that have a good existing road connection and possibly a railway connection too. In populated areas terminals can be located within industrial areas that may already have ongoing similar activities. Road connections are usually available, as well as other services (electricity, illumination, waste management, road maintenance during winter). An existing unutilized asphalt or paved area significantly lowers the terminal establishment costs.

Co-operation with other local companies within the industrial area might also turn out to be beneficial. This co-operation might include maintenance services, combined use and ownership of loading equipment and combined employment of personnel.

### **3.3.3 Terminal capacity**

The size of the terminal can be determined by the annual material output from the terminal to power plants (TWh/a, m<sup>3</sup>/a). In the planning phase, the area requirement of the terminal has also to be defined. This is affected by the selected operation model (rotation times of storage, storage area requirements for ready-made fuel (chips and hog fuel) and storage space for raw materials delivered from the forest. While estimating the area requirements, the space needed for truck/loader passageways and chipper/crusher machinery and conveyors must also be considered.

The main limitations for the terminal operations are set by the local forest and agro-biomass availability and on the other hand the fuel demand of local power plants (e.g. volumes set in the annual delivery agreements). These are also naturally affected by other regional factors: other biofuel users and suppliers and their effects on the regional availability/demand of forest and agro-biomasses. The size of the raw material procurement area and location of the users affect the fuel costs at the plant gate and profitability of the terminal supply chain as whole.



As the annual fuel flow and terminal operation mode are determined, the machinery for the terminal can be sized. Year-round operation often facilitates the use of stationary equipment, while seasonal, periodical operation can be optimally executed with mobile machinery. High utilization rate is crucial for stationary machines with high capital costs, thus at least a two-shift operation would be beneficial for the favourable economics of stationary machines.

### 3.3.4 Terminal area requirements

The terminal area requirements are determined by the amounts of stored fuel and raw fuel material, and storage times. Additional space is needed for machinery and passageways. When the terminal layout is being designed, the location of stationary chipper/crusher is crucial since it will be the key point for both raw material feed and fuel output. There must be enough space for trucks or train carriages to be emptied directly for comminution, and enough space for ready-made fuel to be loaded directly from the extraction conveyor or to be temporarily stored near the machinery. Examples of the space requirements of stationary and mobile machinery are presented in Figure 6. The examples below are good illustrations of current and future terminals.



Figure 6. Examples of the space requirements of comminution machinery in a terminal. A large stationary chipper on the right and mobile chipper on the left. The mobile machinery requires significantly less space as the worksite moves along the piles being processed.

In the case of stationary machinery, the size of the available temporary storage volume for the ready-made fuel is limited by, for example, the dip height and hinge radius of the extraction conveyor or by the volume of the fuel storage pockets. The material flow out from the terminal sets the specification for the sizing of these facilities.

When mobile machinery is applied in comminution, the use of space has to be carefully designed. The mobile machines are able to move and operate beside the

storage piles and the feeding of the machinery can be executed with the loader of the chipper or the crusher, or with a loader of a forwarder or a truck. If the comminution machine is equipped with a long telescopic lifting drag chain conveyor, the size of intermediate chip storage can be increased.

Figure 7 presents a schematic layout of a 1 hectare terminal area, with raw material piles at the sides and ready-made fuel storage in the middle. The sizes of the piles are as follows: raw material pile length 40–75m, width 6m, height 5m. Ready-made fuel storage: length 75m, width 15m and height 7.5m. (Impola & Tiihonen 2011)

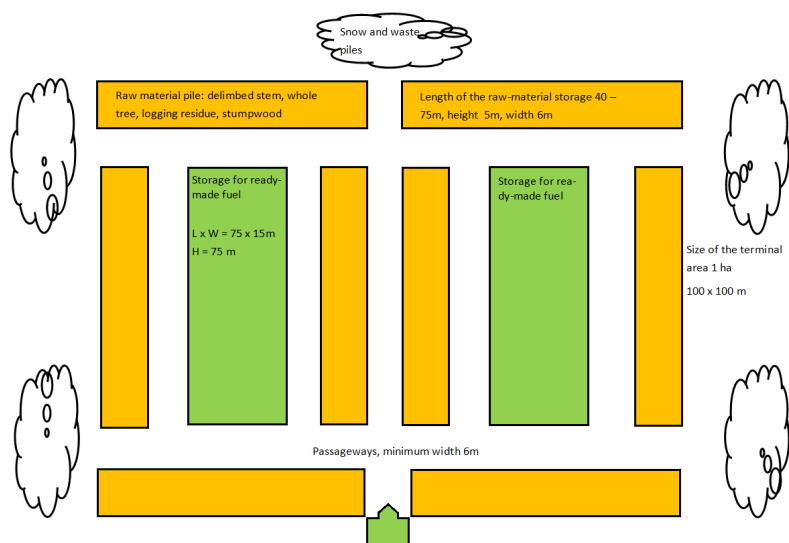


Figure 7. An example of a terminal layout and storage area requirement: the placement of storage for raw fuel material and ready-made fuel when mobile comminution machinery is applied. (Impola & Tiihonen 2011).

With the sizing and layout above 7 GWh of chips or hog fuel can be stored in the terminal at any one time. In addition to this, as stem wood the maximum storage capacity in a 1 ha terminal area is 14 GWh. If the material is stored as logging residue, stumps or as whole trees, the energy content of the stored material is significantly lower, 7–10 GWh due to lower density coefficient. A sizing rule of thumb for planning terminal storage is around 2 MWh/m<sup>2</sup>. Truck transportation and the operation of chippers and crushers require at least 6m wide passageways. The raw material storage can be filled simultaneously as the storage spaces are being emptied.

The space needed for storing certain amounts of raw fuel material depends on the height and shape of the piles as well as the density of the material, for example, how much material in solid-m<sup>3</sup> or MWh can be fitted into a certain area. Table 1 presents space requirements for different raw materials with different density coefficients. From the table it can be seen, for example, that 2–2.5 times more delimbed stems can be fitted into the same area compared to logging residues (it is expected that the storage piles are the same size and shape).

Table 1. Storage space requirement for different raw materials with expected density coefficients. The measurements of the storage piles are: width 6m, height 5m and width of the passageway between piles 6m. (Values modified from Impola & Tiihonen 2011)

Density coefficient solid-m <sup>3</sup> /loose-m <sup>3</sup>	Terminal storage capacity				
	Raw material type	solid-m <sup>3</sup> /m <sup>2</sup>	MWh/m <sup>2</sup>	GWh/ha	Area requirement, m <sup>2</sup> per 1 GWh
0.7	Pulpwood	1.75	3.5	35	286
0.6	Pulpwood	1.5	3	30	333
0.5	Delimbed stem	1.25	2.5	25	400
0.4	Chips/stem wood/bundles	1	2	20	500
0.35	Whole tree/stump wood	0.875	1.75	17.5	571
0.3	Whole tree/stump wood	0.75	1.5	15	667
0.25	Logging residues	0.625	1.25	12.5	800
0.2	Logging residues	0.5	1	10	1000

Space requirement for different energy contents of stored fuel is displayed in Table 2.

Table 2. Storage space requirement (hectares) for different raw materials with expected density coefficients and different amounts of stored fuel. The measurements of the storage piles are: width 6m, height 5m and width of the passageway between piles 6m. (Values modified from Impola & Tiihonen 2011)

Density coefficient solid- m <sup>3</sup> /loos e-m <sup>3</sup>	Size of the terminal storage (GWh)							
	Raw material type	50	100	300	400	500	800	1000
<b>0.7</b>	Pulpwood	1.4	2.7	8.6	11.4	14.3	22.9	28.6
<b>0.6</b>	Pulpwood	1.7	3.3	10.0	13.3	16.7	26.7	33.3
<b>0.5</b>	Delimbed stem	2.0	4.0	12.0	16.0	20.0	32.0	40.0
<b>0.4</b>	Chips/stem wood/bundles	2.5	5.0	15.0	20.0	25.0	40.0	50.0
<b>0.35</b>	Whole tree/stump wood	2.9	5.7	17.1	22.9	28.6	45.7	57.1
<b>0.3</b>	Whole tree/stump wood	3.3	6.7	20.0	26.7	33.3	53.3	66.7
<b>0.25</b>	Logging residues	4.0	8.0	24.0	32.0	40.0	64.0	80.0
<b>0.2</b>	Logging residues	5.0	10.0	30.0	40.0	50.0	80.0	100.0

The height of the storage piles has a very strong effect on the space requirement of the terminal. If the height of the piles is reduced to 4 metres, 25% more storage area is required to fit the same energy content of fuel (height increment to 6 metres leads to 20% volume capacity increment). If 5 meter wide passageways can be applied, the storage area requirement for the same amount of energy is reduced by 8.3%. The change in the width of the storage pile does not have as large an effect as height; if the width of the storage is reduced from 6 to 5 metres, the space requirement for the same energy content of the storage is increased by 10%.

It has to be noted that the examples above are theoretical in the sense of the shape of the storage piles. In practice, the piles are not rectangular but conical. This is the case especially with chips, logging residues and stumps. If the cross-section of the pile is exactly triangular, the space requirement is doubled compared to rectangular storage piles. With round wood, especially delimbed stems, close to rectangular storage pile shapes can be obtained.

Other important point is that in raw fuel material storages, passageways are not always needed, as the material can be stored in piles side by side and the storage can be distributed from one side, usually from the “older end”. When applying this

type of storage scheme, it must be noted that without passageways the drying of the fuel material will not be as effective as with passageways going through the storage providing effective drying air flow.



Figure 8. With good planning and especially by maximizing the height of the storage piles, the area needed for storage can be minimized. With proper foundations of the piles and with adequate passageways the drying and preservation of the material can be optimized.

### 3.4 Terminal planning

As the establishment costs of a terminal are rather high and the lifetime of a terminal should be as long as possible, good initial planning regarding space arrangements is required. Examples and experiences of existing terminals compared to what is needed in the new terminal are a valid starting point. Below is a list of aspects that influence the technology choices and the profitability of a terminal that should be considered when planning a new terminal (Impola & Tiihonen 2011):

- Business models of the terminal
- Possible co-operative partners
- Geographical and regional location of the terminal
- Area and capacity of the terminal
- Storage (raw material and fuel) and production capacity requirements
- Environmental effects and licencing
- Regional raw fuel material potentials
- Regional fuel demand (heat and power plants in the region)
- Transport modes for produced fuel
- Terminal equipment and machinery
- Layout of the terminal area
- Investment and operational costs of the terminal
- Profitability and alternative operation modes

As the amount of produced fuel is known on a yearly, monthly and daily basis, the required production and handling of machinery can be calculated based on the capacities of the machinery. The minimum terminal area can be estimated by the space requirements given in the previous chapter. It is beneficial to have at least an area of additional space reserved in case the terminal activities increase during the lifetime of the terminal and additional storage area is needed.

### **3.5 Biomass drying in terminals**

Moisture in biomass fuels can cause many undesired effects in combustion. Moisture decreases the heating value of the fuel that lowers the adiabatic combustion temperature. Flue gas flow increases with increasing moisture. This results in a higher power-need for flue gas fans and this lowers the efficiency of the plant. The dew point of flue gases also increases with the increasing moisture content in the fuel. Moist fuel causes more fouling in the combustion chamber compared to dry fuel. Low-moisture fuel has a positive effect on the dimensioning of process equipment when designing new processes (Motiva 2014).

Drying increases the heating value of the fuel. If the fuel is sold from a terminal based on euros per MWh, more income is gained from same amount of delivered fuel measured per volume unit (solid-m<sup>3</sup>). A price of 20 €/MWh was assumed for the value of delivered fuel. For example, for the annual delivery volume of 200 000 solid-m<sup>3</sup>/year gross benefit from artificial drying is around 750 k€/year due to the increase in the heating value from 7.3 MJ/kg (55 m-% moisture) to 11.7 MJ/kg (35 m-% moisture). However, when the net profitability is studied, the increased value of delivered fuel must cover all expenses relating to the terminal storage area, capital tied to storage, handling of material to and from the dryer, biomass dryer investment and operational costs of the dryer.

#### **3.5.1 Natural drying**

Moisture content of fresh forest biomass fuel is typically 40–55 m-%. The moisture content varies depending on the time of year. Moisture also varies between different parts of a tree. Due to the high initial moisture content of forest fuel, raw material is typically left in the forest to dry. The typical time for this natural drying is approximately 3–6 months. Natural drying is an economical drying option since the only costs generated relate to capital tied to storage. (Motiva 2014)

Natural drying also takes place in a terminal during the storage of raw fuel material over the spring and summer months. Ready-made fuel may be dried by spreading the fuel chips or hog fuel onto an open asphalted area. The benefit gained from this is the increased energy content of the fuel. In addition to capital costs related

to capital tied in storage, costs may incur from additional handling of fuel and increased terminal area requirements.

### 3.5.2 Basics of artificial drying

Streamlining the wood fuel chain supply-chain of raw wood fuel material could be referred to as fast-track supply of wood fuel. Shorter delivery times are reached by utilizing artificial drying. In this study it was assumed that financial benefits of the the fast track supply are gained through improved heating value of the dried fuel (more energy per unit volume of fuel) and through faster delivery time of the raw material (decreased capital costs).

There are many ways to classify different types of artificial drying technologies. Here we focus on low-temperature technologies (air drying media) that are likely to be more suitable for raw material terminals than high-temperature drying technologies (for example, flue gas or steam drying media). Specific energy consumption for air drying depends, for example, on the drying technology, temperatures (ambient, drying and raw material), process connections and many more. Theoretical value for the specific heat consumption for air drying is approximately 2.7–2.9 MJ/kg of evaporated H<sub>2</sub>O. In practice typical specific energy consumption depends heavily on ambient air temperature, and in Finland this is typically in a range of 4–6 MJ/kg H<sub>2</sub>O. (Motiva 2014)

When raw fuel material dries, water that is on the surface and on the inside of the raw material evaporates. If the drying media is air then the drying process can be described with the Mollier diagram of air, see Figure 9. Atmospheric air (1) is heated prior to drying in order to increase amount of evaporated water that it can absorb. The air is heated to the point (2). The air cools down during the drying process to the point (3) in the Figure. Relative humidity of the drying air would be 100% when leaving the process ( $x_{\text{theoretical}}$ ) in the Figure but in practice its relative humidity is less than 100% ( $x_{\text{real}}$ ). Increase in temperature of drying air decreases the amount of air needed for drying. This results in less power needed for air fans and lower specific heat. The investment cost of a dryer decreases with increasing temperature of drying air due to a more compact structure of the equipment. Heating of drying air can be done in one or multiple phases. Optimization of the drying process typically includes optimization of the amount of heat and power needed for air fans.

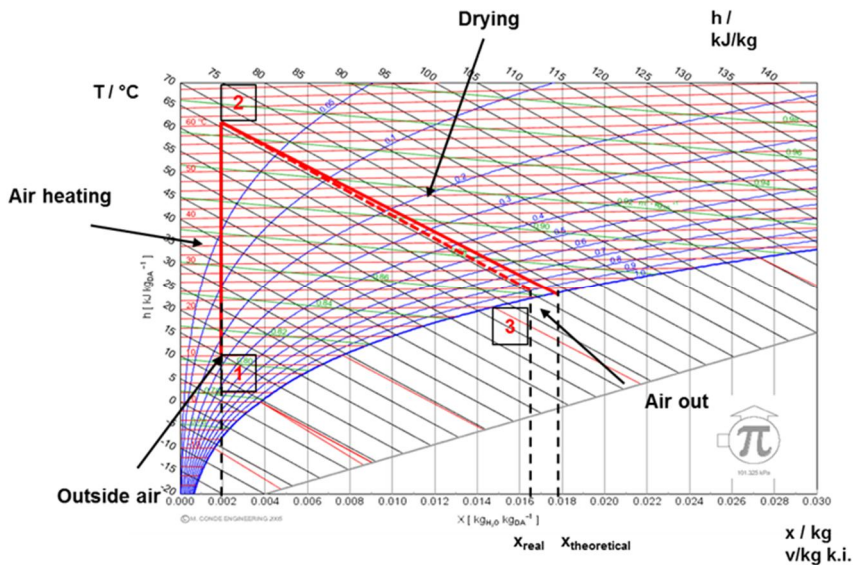


Figure 9. Mollier diagram of air.

Currently biomass drying in terminals is marginal if not non-existent. In some cases fuel is dried in connection to fuel receiving at plant. The main challenge so far has been the availability of heat (which should be available at no cost) in terminals remotely located and without heat and power sources

### 3.5.3 Covered field dryer

Artificial drying for a capacity of 200 000 solid-m<sup>3</sup>/year was studied. It was assumed that raw material would dry from 55 to 35 m-%. Covered field drying and belt drying were studied due to their ability to utilize low-temperature heat. The initial hypothesis was that these could be the most financially feasible drying options. Technological soundness and feasibility were studied briefly during the course of the study.

Field drying is a technology that is widely used. It typically utilizes natural solar radiation, therefore it is mostly limited to the summer season in Finland. A possibility to cover the drying field was also studied in order to enable its function during the winter time (Figure 10).



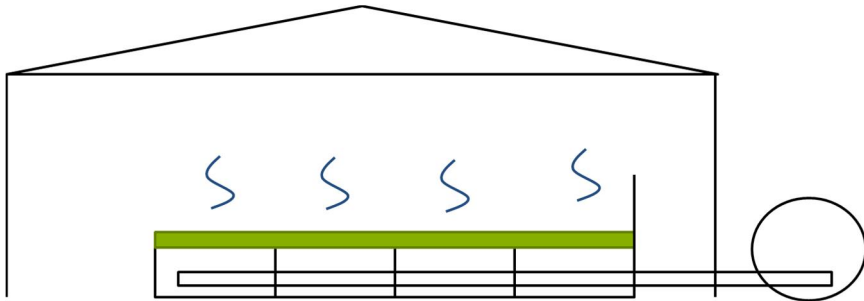


Figure 10. An illustration of covered field drying.

It was assumed that there would be zero-cost heat at 60°C available in close vicinity to a terminal. To dry 200 000 m<sup>3</sup>/year of raw material from moisture of 55 m-% to 35 m-% would require 2 fields, each one 200 x 20m in dimensions. A bed height of 0.2m was assumed. If annual operation hours were 7500 h/year that would equal an evaporation of 7.4 tonnes/hour of water on average. The maximum residence time for drying would be approximately 39 hours, which should be adequate for the studied drying purposes. Heat needed for drying would be approximately 11 MWth (drying efficiency 85%).

The required construction work and building turned out to be costly. A rough estimation of the investment was approximately 6.1 M€ Annual operation and maintenance costs were estimated at around 650 k€/year. Therefore it is challenging to find economic justification for development of this these type of constructions. There would also be certain challenges regarding, for example, the process of loading and unloading of the batch, and possible heat losses of the process. If the time required for drying was significantly less than 39h that might reduce the cost of the building. Smaller sized buildings would also make the process of loading and unloading easier. Optimization of both the structures and the process would be needed to find the most cost efficient solution.

#### 3.5.4 Belt dryer

Another alternative that was studied included a belt dryer (Figure 11) adjoined to a heat pump. It was assumed that the same zero-cost low temperature heat (i.e. 60°C) would be available. The heat would be provided for the dryer at two temperature levels, namely at 60°C and at 85°C. With annual operating hours of 7500 h/year the primary heat source (i.e. 60°C) would provide approximately 5.5–7.5 MW of heat. In this case the secondary source of heat would only need to provide approximately 3.7 MW of heat. The latter heat would be provided by a heat pump. Using typical costs for the belt dryer and the heat pump the investment cost would be approximately 4.4 Meur. Operating costs were estimated at approximately 450 k€/a. A COP of 5 and 45 €/MWh of electricity were used. In addition to electricity, which contributes a major part of the operating cost, one operator and an annual

maintenance cost of 1% of the investment was assumed. If faster rotation of inventory was taken into account (6 month faster delivery of the raw fuel material compared to current times, 10% interest) payback time for the process would be approximately 6.7 years. It has to be noted that the figures presented are preliminary and actual costs would very much depend on local circumstances.

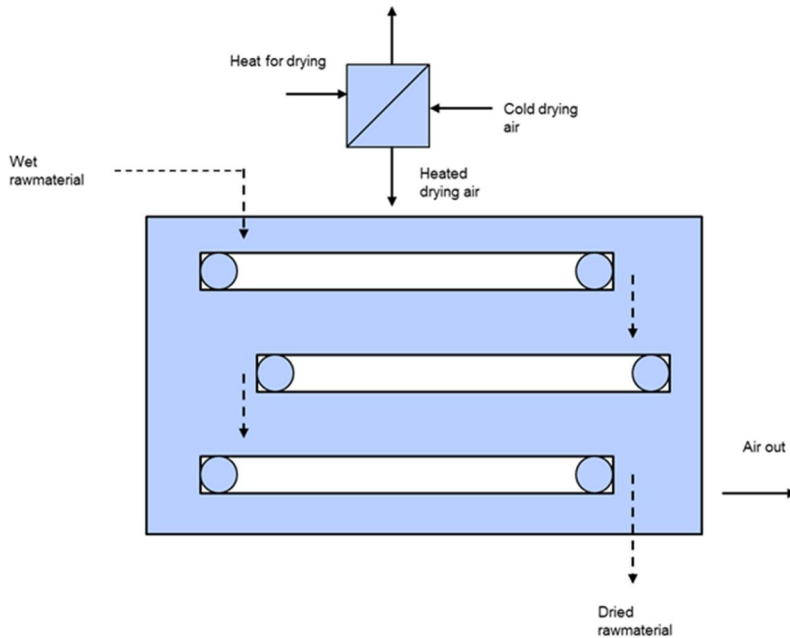


Figure 11. An illustration of a multi-layer belt dryer.

Availability of the zero-cost heat limits possibilities for suitable locations of the terminals that would have a dryer similar to the studied cases. These suitable locations might be challenging to find but most could be located next to pulp mills and other types of mills with excess heat from cooling. Some power plants might also serve as an attractive possibility. Process connections with a heat pump might enable a lower temperature for returning district heat water that would enable better power production efficiencies at the power plant. However this is case-specific and it should be designed according to local circumstances.

## 4. Developing terminal concepts

### 4.1 Organization of fuel supply through terminals

There are basically three different operation models for organizing the supply that can be applied to all terminal concepts: energy company model, supply company model and operator company model.

In the **energy company model**, the energy company buys wood standing or at the roadside and purchases procurement operations from subcontractors. The material is transported to the energy company's own terminal where processing takes place. All processing and handling services are purchased from contracting operators. Fuel is then delivered to the energy company's usage sites. All fuel during the whole supply chain is owned by the energy company.

In the **supply company model**, the supply company buys wood standing or at the roadside and delivers the fuel to its own terminal (harvesting and transport subcontracted). All procurement, handling and processing and delivery to user sites according to supply contracts are executed by the subcontractors of the supply company. Here the supply company's role is merely organization of fuel purchases, management of supply and sales and deliveries to users.

In the **operator company model**, the operator buys wood standing or at the roadside, harvests and transports the fuel to its own terminal, carries out required processing and handling and sells and transports the fuel to users according to supply contracts.

It is important to note that tied capitals are rather large in the wood fuel supply business, especially when it comes to storing wood fuel on a large scale. This has led to a situation where the energy company model dominates. The explanation is rather easy, though. In this model, tied capital is the capital of the fuel end user company and thus all the purchased wood fuel has a "target" without a complex supply contract and risk to a separate supply company. In other words, acting through the energy company model the energy company manages its own risks by

having sufficient storage and outsources all procurement and processing to sub-contractors.

## **4.2 Identified developing terminal types**

The following chapters present the 3 identified terminal concepts (satellite terminal, feed-in terminal and fuel upgrading terminal) identified in this study. Examples of satellite and feed-in type terminals from Sweden can be found, and the descriptions given in the report are mostly based on these existing real-life examples. A fuel upgrading terminal is a special case of a satellite or feed-in terminal, where the form of upgrading can be, for example, sieving, drying, briquetting or pelletizing. Where longer storage of raw fuel material is expected, the stored material is often delimbed stem or large-sized uncommercial stem wood due to its good storage density, easy handling and minimal dry matter losses during storage.

### **4.2.1 Satellite terminal**

Satellite terminals are more complex and developed fuel processing and storage sites. The descriptive feature of satellite terminals is that they are located near the fuel resources, away from the usage sites. Common annual fuel flow can be expected to be up to 1 TWh/a (500 000 solid-m<sup>3</sup>/a).

Large material volumes require large areas; the common space requirement is close to 10 hectares of asphalted area for operating machines, raw fuel material and ready-made fuel storage. The terminal operates year round, heating season being the most active period. Satellite terminals are expected to serve large, often distant customers, thus a railway connection is essential in addition to road connections. The high security of fuel supply is assured by storing raw fuel material for the high season (season storage). Near storage is short term storage for fuel near comminution machinery, which is filled up by arriving trucks and internal terminal material transfers. Low unit costs of processing can be achieved by utilizing large purpose-built machines with high utilization rates. A 6 meter storage pile height can be expected, because material handling machinery is expected to be utilized in the storage management. This facilitates greater storage capacity (20%) per storage area unit compared to traditional terminals with a 5m pile height.

Measurements of in- and outgoing-material in satellite terminals are based on weigh bridges. Additional mass measurements can be executed by the loader scales of the operating machines.

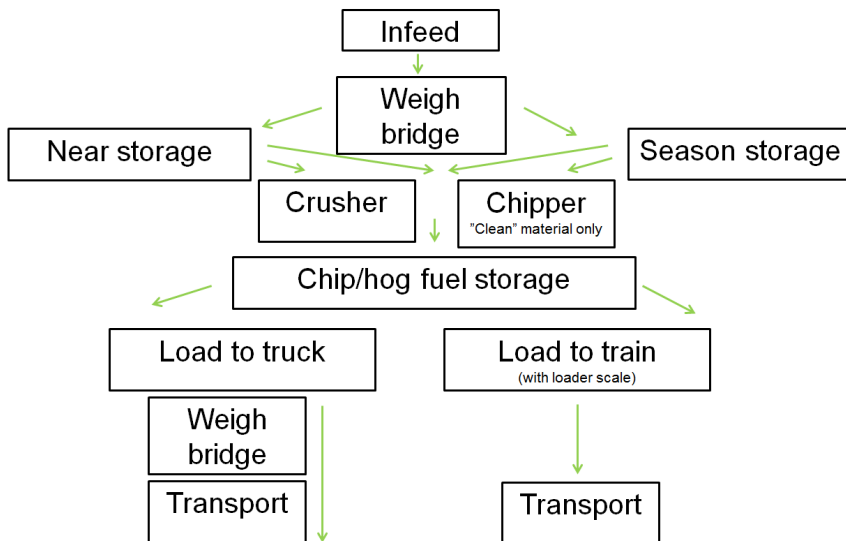


Figure 12. Chart layout of a satellite terminal.

The layout of the satellite terminal was studied in more detail and the initial layout presented in Figure 13 was created. The key parts of the terminal are season storage, near storage and storage space for ready-made fuel.

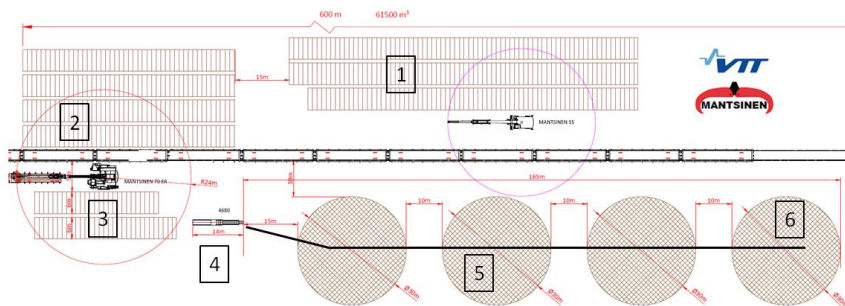


Figure 13. Layout example of a satellite terminal. 1. Season storage of raw fuel material. 2. Near storage of raw fuel material near comminution machinery. 3. Material handling machine for the unloading of trucks and feeding of comminution machines. 4. Chipper/crusher. 5. Fuel conveyor. 6. Loading area for departing trucks and trains.

Figure 13 represents a case where all material is transported to the terminal by trucks. If railway transports are applied for incoming material or the annual fuel flow requirements exceed the capacity of one loading train per working shift ( $> 2400 \text{ loose-m}^3$ ), additional tracks would be needed. Figure 14 presents an exemplar track layout of a larger terminal, with several loading tracks. This layout also

facilitates the handling of commercial timber in the terminal in addition to wood fuels and raw wood fuel materials.

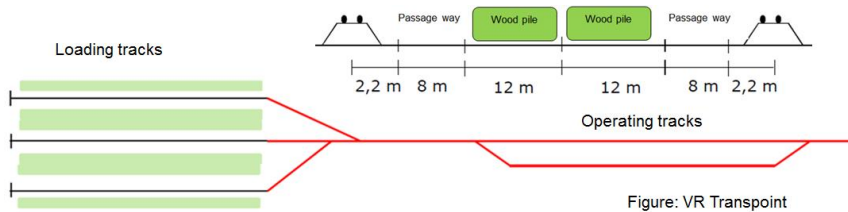


Figure: VR Transpoint

Figure 14. Example of a terminal track layout with several loading tracks (VR transpoint).

An example of a satellite terminal is presented in Figure 15. Stockarydsterminalen AB operates a satellite terminal in Sävsjö, Sweden. The terminal is area is divided between two operators, the above mentioned terminal company operates on the right side and the left side is operated by Stora Enso. Both wood fuel and commercial timber are processed and handled in the terminal by both operators.



Figure 15. Satellite terminal Stockarydsterminalen in Sävsjö Sweden (Figure: intelligentlogistik.se).

Compared to a traditional transshipment terminal a satellite terminal provides year round possibilities for large scale biomass handling and processing. With suitable output (> 0.5 TWh) a special purpose built material handler becomes an economical option. Large volumes also make the terminal less sensitive to the cost effects of terminal equipment investments (sieves, material quality control devices, conveyors, compaction machinery). Thus, if a price premium is offered for more processed fuel, there are possibilities to react to this demand.

#### 4.2.2 Feed-in terminal

The main function of a feed-in terminal is the balancing of fuel supplies to a heat or power production facility. The motivation for utilizing a feed-in terminal is usually based on insufficient receiving and storage facilities in the plant site and supply security reasons. Feed-in terminals are often located near a usage site and both ready-made fuel (short term) and raw fuel material (stem wood, possibly also stumps) are stored. The storage sites act as a buffer in case there are difficulties in fuel supply due to weather conditions or other temporary problems. The expected annual supply capacities are expected to range from 0.7 to 1 TWh.

It must be stated that in an optimal case supply through a feed-in terminal should be avoided. If additional loading/unloading sequences are needed, the cost of the fuel supply also increases. However, the security of supply and balancing of annual fuel deliveries and potentially also supply costs have motivated many energy companies to utilize feed-in terminals.

The fuel demand of the plant drives the operation of the feed-in terminal. In a large-scale operation with long-haul supply deliveries a railway connection is crucial. Optimally, a railway link to the plant would be available. However, in many cases the trains are unloaded at the feed-in terminal and further transports are executed with fuel trucks.

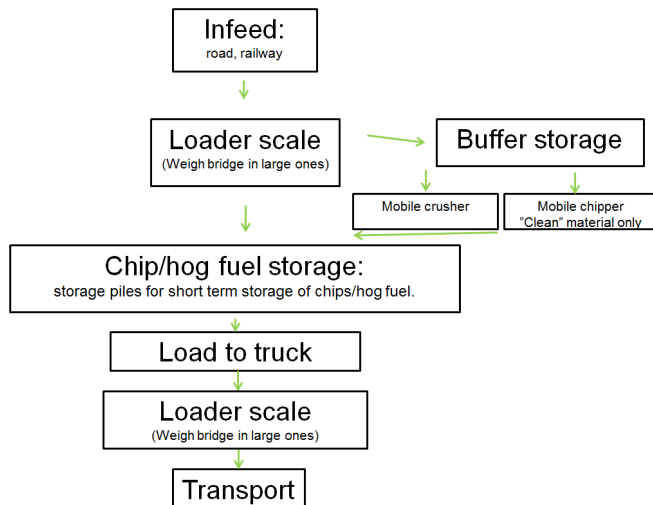


Figure 16. Schematic layout of a feed-in terminal.



Figure 17. Söderenergi's feed-in terminal in Nykvarn, Sweden. Storage of ready-made fuel on the left, loading rail in the middle and buffer storage of stem wood on the right.

The Söderenergi's terminal receives wood fuels both by rail and road transportation. All fuel is transported by trucks to a power plant located in Södertälje 10km from the terminal.

#### **4.2.3 Fuel upgrading terminal**

The fuel upgrading terminal is a special case of feed-in or satellite terminal. The applied fuel upgrading processes rely on the needs of the customers and also on the available resources such as heat for drying.

Possible ways of upgrading fuel include artificial or natural drying (post or pre comminution), sieving, blending and densifying (post comminution). Chapter 3.5 "Biomass drying in terminals" presents the drying options and the economics of artificial drying in more detail. An additional example of a natural biomass terminal is given in Figure 20b.

It is worth noting that the mere storing of raw wood fuel material can be regarded as fuel upgrading. During the summer seasons the material dries and then, with the declining moisture content, the energy content increases. When considering the economic benefits of drying the costs of tied capital in storages as well as the cost for the occupied terminal area must be carefully considered.



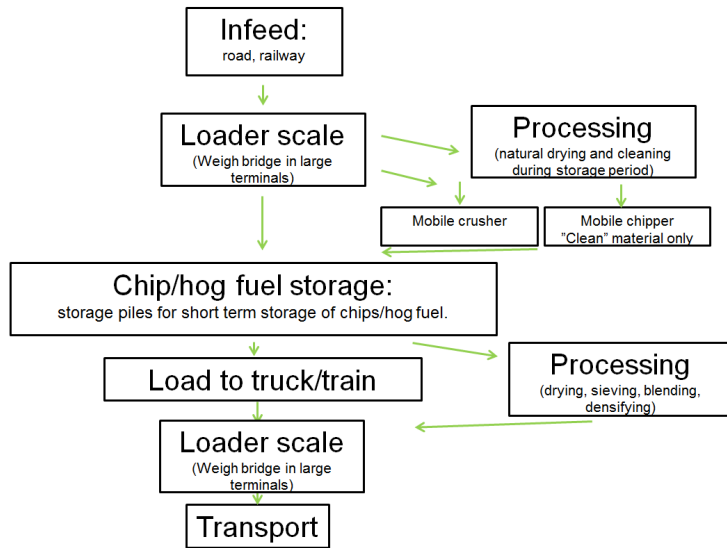


Figure 18. Schematic layout of a fuel upgrading terminal.

## **5. Case study: satellite terminal cost analysis**

### **5.1 Satellite terminal cost analysis methods and calculation principles**

The satellite terminal was selected for cost analysis due to its complex structure that exhibits all required work phases and sources of terminal supply costs that must be considered, and also due to the satellite terminal's key role in long haul wood fuel supply chains. Four different annual fuel outputs were selected for analysis: 0.1, 0.3, 0.7 and 1 TWh/year of supplied fuel. The three largest size classes (0.3, 0.7 and 1 TWh) are based on a train transport sequence: for 1 TWh/a there are two daily chip train departures. For 0.7 TWh/a one daily chip train departure is sufficient and for 0.3 TWh/a a train departs every second day. The 0.1 TWh/year was selected to reflect the effect of terminal size to fuel treatment and handling costs. A conversion factor of 2 MWh/solid-m<sup>3</sup> is applied in the following calculations in case no other value is given.

#### **5.1.1 Terminal area and logistical connection related costs**

Terminal area related costs consist mainly of terminal land acquisition costs and land construction costs. The land cost varies from one site to another and it is very hard to give even a regional average on the purchase cost of land area. In addition to purchasing land, terminal sites can also be rented or leased. A common value in rural areas for terminal area rent has been 1000€/ha/year.

Land construction is also a significant cost element. The asphaltting cost for an existing gravel surface costs around 20–30 €/m<sup>2</sup>. If additional land construction work has to be done before paving the area, the total cost can be over two or three times higher compared to mere paving cost of the area.

The construction of connecting roads and railways also generates significant costs. In many cases these logistical connections are, however, not constructed by the terminal operator, or at least the construction is strongly subsidized. Table 3 summarizes key land construction costs.

Table 3. General land construction costs (RIL 2006).

Connecting road, width 7m	320	€/m
Forest road	35	€/m
Parking area	84	€/m <sup>2</sup>
Asphalt paved area	62	€/m <sup>2</sup>
Gravel paved area	47	€/m <sup>2</sup>
Railway track	1100	€/m
Railway track switch	79 000	€/piece
Noise protection wall, 4m high	200	€/m
Groundwater protection	21	€/m <sup>2</sup>

In this study a terminal site acquisition cost was expected to be 5000 €/ha, paving cost 30€/m<sup>2</sup>, service life of the area 15 years, interest rate 10% and the residual value of the area 5000€/ha. 50% of the total terminal area was expected to be paved with asphalt. No road, railway or other land construction costs were included in the calculation. Figure 19 presents additional unit costs generated from terminal land acquisition and terminal land construction (A&LC, €/m<sup>2</sup>) for different terminal outputs.

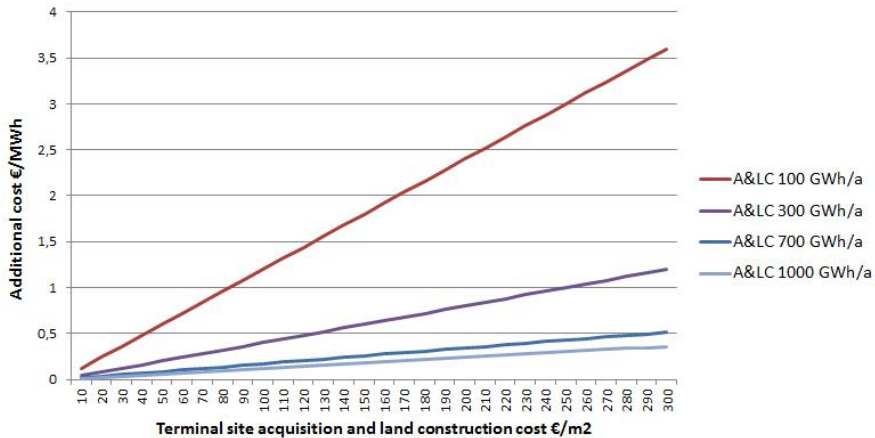


Figure 19. Unit costs generated from terminal land acquisition cost and land construction cost (€/m<sup>2</sup>) for different terminal outputs (A&LC = acquisition and land construction).

### 5.1.2 Fuel storage costs: tied capital, dry matter losses and terminal area management

Capital tied in terminal storage generates significant costs, but on the other hand storage is a way to increase security of supply and improve the quality and value of the fuel through natural drying. In this study a 10% interest rate was applied for all material stored in season storage (long term storage of raw wood fuel material). The capital cost was not estimated for ready-made fuel or for raw fuel material in feed-in storages (operative short term storage near a comminution site), due to short lag time of the material between processing and transport to user.

Figure 20a presents the gross added value for 1 hectare of terminal storage area when the stored material dries from a maximum of 55% MC to a minimum of 30% MC. The added value is based on the stored volume (solid-m<sup>3</sup>) that fits to a 1 ha area with different raw fuel material densities (from 0.7 solid-m<sup>3</sup>/loose-m<sup>3</sup> for uncommercial stem to 0.2 solid-m<sup>3</sup>/loose-m<sup>3</sup> for logging residues). The expected value of the material is 21 €/MWh.

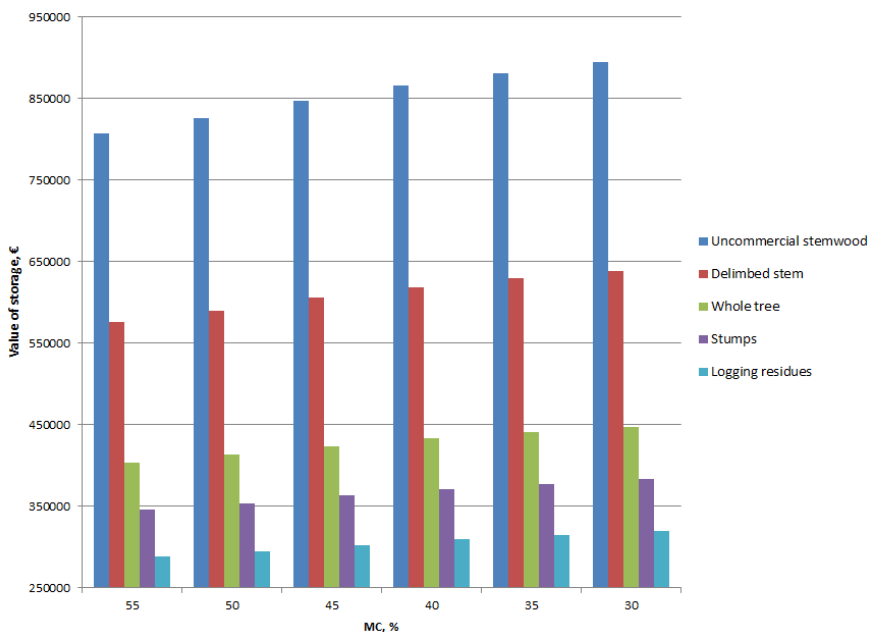


Figure 20a. Gross value added based on the drying of biomass in 1 ha terminal area for different raw fuel materials (no costs related to storing taken into account, 6m high storage piles).

The figure shows that with uncommercial stem wood the value of storage is increased from €807k to €894k, with delimbed stem from €576k to €638k with whole tree from €403k to €447k with stumps from €345 k to €383k and with logging residues from

€288 to €319k. The figures indicate that the more material can be fitted to a storage area unit (hectare, between 42 GWh with uncommercial stem wood and 12 GWh with logging residues) the more added value can be created through drying of the material.

As presented above, storing increases the value of fuel. However there are costs to be taken into account when studying the net profitability of fuel storage i.e. costs of storage versus gains from increased energy content of the fuel.

Figure 20b presents an exemplar situation where material is stored for a total of 6 months, over the summer season. Stored volume is 21 000 to 7500 solid m<sup>3</sup>, depending on the density of the material (stem wood vs. logging residues) and thus the volume capacity per one hectare (table 3). Storage losses are expected to be at the level of 0.5% per month and area management and maintenance cost 3000€/year. The expected gain is generated through the energy content increment of the stored material (MC is decreased from 55% to 35% during storage, and energy content per solid-m<sup>3</sup> is increased from 1.813 MWh/m<sup>3</sup> to 1.998 MWh/m<sup>3</sup>). The value of the stored material is expected to be 21 €/MWh. When costs are deducted from the expected gain, it can be observed that storage is economical only when the acquisition and land construction cost is below 5 €/m<sup>2</sup> or 50 000 €/ha (logging residues) and below 20 €/m<sup>2</sup> or 200 000 €/ha for uncommercial stem wood.

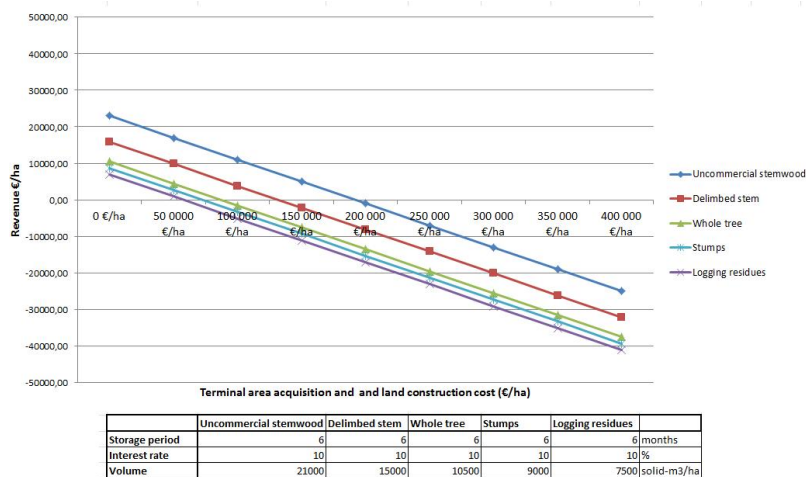


Figure 20b. Revenue/loss calculation for stored raw fuel material based on material drying in storage from 55% MC to 35% MC. Interest rate 10%, storage time 6 months, stored volume 21 000 to 7500 solid-m<sup>3</sup> depending on raw fuel material.

The storage area requirement in 1 and 0.7 TWh terminals for different raw fuel materials and terminal sizes is based on the figures given in Table 4. Expected width of the storage pile is 6m, height 6m, and width of the passageway between

piles is 6m. The 1 meter height increment compared to 5 meter height presented in table 1 results in 20% more storage capacity per storage area hectare.

Table 4. Storage space requirement for different raw materials with expected density coefficients. The storage pile measurements of the storage piles are: width 6m, height 6m and width of the passageway between piles 6m. (Values modified from Impola & Tiihonen 2011)

Density coefficient, solid-m <sup>3</sup> /loose-m <sup>3</sup>	Raw material type	solid-m <sup>3</sup> /m <sup>2</sup>	MWh/m <sup>2</sup>	GWh/ha	MWh/ha	m <sup>2</sup> /GWh
0.7	Pulpwood	2.1	4.2	42.0	42000	238.1
0.6	Pulpwood	1.8	3.6	36.0	36000	277.8
0.5	Delimbed stem	1.5	3.0	30.0	30000	333.3
0.4	Chips/stem wood/bundles	1.2	2.4	24.0	24000	416.7
0.4	Whole tree/stump wood	1.1	2.1	21.0	21000	476.2
0.3	Whole tree/stump wood	0.9	1.8	18.0	18000	555.6
0.3	Logging residues	0.8	1.5	15.0	15000	666.7
0.2	Logging residues	0.6	1.2	12.0	12000	833.3

For 0.3 TWh and 0.1 TWh terminals 5 meter pile height was expected and thus figures given in Table 1 were applied.

In addition to area requirement of raw fuel material storage piles, other auxiliary areas for example chipping and crushing are needed. The expected area for comminution equipment was 0.7 ha, and two respective areas for two comminution machines were expected for 0.7 and 1 TWh terminals. Area of related near storage (operative short term storage for raw fuel material near comminution site) was 0–0.4 ha and chip storage are 0.1 to 0.2 ha. Total terminal space requirements for 0.1 to 1 TWh terminals vary from 0.9 to 6.2 ha respectively. Table 5 presents the area requirements for different terminal outputs. Space requirements for connecting road and railways are not included due to their case specific nature.

Table 5. Area requirements for different terminal outputs in hectares. Connecting roads and railways not included in the calculation.

Output, TWh	Season storage area, ha	Near storage area, ha	Crusher/chipper + auxiliary areas, ha	Chip storage, ha	Total area excl. connecting roads & rails, ha
1	4.3	0.4	1.3	0.2	6.2
0.7	2.9	0.2	1.3	0.2	4.6
0.3	1.7	0.1	0.7	0.1	2.6
0.1	0.5	0.0	0.3	0.1	0.9

The above-mentioned space requirements can only be applied if certain distribution for material between storage is applied. In this study it was estimated that 31% of the material is processed through season storage. 43% of the material is processed through near storage. 26% of the material is fed directly to comminution from trucks or train carriages. This distribution is based on actual case experiences from a pulpwood terminal, cost optimization of material handling between different storage options and estimations on requirements of security of supply for a biomass fuel terminal.

The applied rotation times for season storage and near storage are 2 rotations/year and 100 rotations/year respectively. Table 6 presents the annual fuel flows through different terminal storage (season storage and near storage) and direct feed to comminution. Similar material between storage breakdown was applied for all terminal sizes for achieving comparable results.

Table 6. Annual material flow breakdown for different terminal outputs (1 to 0.1TWh) between season storage, near storage and direct feed to comminution.

Output, TWh	Through season storage, GWh/year	Through near storage GWh/year	Direct feeding from trucks, GWh/year	Total GWh/year
1	312	443	258	1014
0.7	208	295	172	675
0.3	104	147	86	337
0.1	31	44	26	100

Table 7 presents the volume of different storage facilities per one rotation and daily amount of directly fed raw fuel material from trucks or trains.

Table 7. Applied volumes of different storage facilities per one rotation and daily direct raw fuel material feed to comminution.

Output, TWh	Season storage, GWh/rotation	Near storage GWh/rotation	Direct feeding from trucks/trains, GWh/working day	Total GWh/year
1	156	4	1	1014
0.7	104	3	1	675
0.3	52	1	0.3	337
0.1	15	0.4	0.1	100

Table 8 presents the theoretical daily fuel supplies from different storage facilities. In practice the material supply-delivery-distribution is different due to the fact that both raw fuel material supplies and the amount of fuel deliveries vary from season to season and the peak is reached between December and February. However, the theoretical daily amount of supplied fuel helps to give a good concept of the scale of the operation.

Table 8. Volume of daily fuel supply from different storage facilities and daily delivered fuel amount.

Output, TWh	Season storage, MWh/working day	Near storage MWh/working day	Direct feeding from trucks, MWh/working day	Total average MWh/day
1	1237	1760	1026	4022
0.7	824	1172	683	2679
0.3	411	585	341	1337
0.1	122	174	101	397

### 5.1.3 Machine investments and operational costs

For presenting the comminution costs, a cost analysis of 2 different machine options for 0.7 TWh and 1 TWh terminals was executed. The options were a full trailer-based crusher and a stationery chipper. The cost-productivity data was collected from machine manufacturers and machine operators.

The crusher investment includes the chipper unit and a 15 meter discharge conveyor. The chipper unit consists of a feed-in conveyor, metal detector, chipper,



discharge conveyor, foundation, protective buildings and all required installation costs for making the unit operative after it has been delivered by the manufacturer. Applied investment costs were €550 000 (crusher) and 2 million euros (stationery chipper), service lives 3.4 and 15 years respectively. Applied hourly costs 186.6 €/working hour for crusher and 238 €/working hour for chipper. Annual working hours were expected to be 4000 hours, based on a year-round 2-shift operation. Table 9 presents the applied productivities for different fuel materials. Other applied unit costs of comminution are displayed on Table 10. For 0.1 TWh and 0.3 TWh terminals, a crusher was the only studied comminution option.

Table 9. Applied productivities per utilization hour including interruptions shorter than 15 minutes ( $\text{€/h}_{-15}$ ) and unit costs for comminution machinery. Data collected from machine users and manufacturers and from Rinne (2010).

	Uncommercial stem wood	Delimbed stem	Whole tree	Stumps	Logging residues
Productivity MWh/ $\text{€/h}_{-15}$ , mobile crusher	106	106	106	70	120
Productivity MWh/ $\text{€/h}_{-15}$ , stationary chipper	164	164	164	N/A	180
Unit costs, €/MWh, mobile crusher	1.76	1.76	1.76	2.66	1.56
Unit costs, €/MWh, stationary chipper	1.45	1.45	1.45	N/A	1.32

The large 0.7 TWh and 1 TWh terminals provide full work load for comminution machinery. In smaller 0.1 TWh and 0.3 TWh terminals the machines were expected to work periodically on a contract basis, meaning that the machines were moved from one terminal to another depending on their schedule. Thus, compensating for the additional costs incurred from shifting from one work site to another, 10% cost increment was applied for comminution operations in 0.3 TWh terminal. In 0.1 terminal the expected cost increment was 30%. Cost foundation data was collected mainly from manufacturers and from Rinne (2010). In 0.7 and 1 TWh terminals all comminution machines were expected to be electrically powered. In smaller terminals, a diesel powered crusher option was applied. The comminution cost with a diesel option was slightly higher compared to the electrically powered option.

Table 10. Other costs of comminution for a mobile crusher and a stationary chipper.

	Mobile crusher	Stationary chipper	
Insurance	0.011	0.012	€/MWh
Workforce	0.2	0.2	€/MWh
Admin	0.1	0.1	€/MWh
Blades and sieves	0.2	0.3	€/MWh
Maintenance	0.2	0.2	€/MWh
Fuel/energy	0.5*	0.3	€/MWh
Unexpected & budgeted surplus	0.09	0	€/MWh

\*Energy cost with diesel powered crusher 0.55 €/MWh

#### 5.1.4 Material handling machines

In the two larger 1 and 0.7 TWh terminals, material handling machines were expected to be used in the unloading of trucks, storage pile management (near and season storages) and feeding of the comminution machine. The feed-in machine in 0.7 TWh and 1 TWh is an electrically powered 90 tonne material handler with 26 meter reach and a rail undercarriage. The season storage material handler (0.7 TWh and 1 TWh terminals) is a 60 tonne diesel powered material handler with 17 meter reach and a track undercarriage. In the smaller terminals, all loading and feeding was expected to be executed by the loaders of trucks. The applied raw fuel material handling costs are presented in Table 11.

For all terminals, two parallel material management options were studied: feed through season storage and direct feed to comminution. These two material handling procedures are displayed in Figure 21.

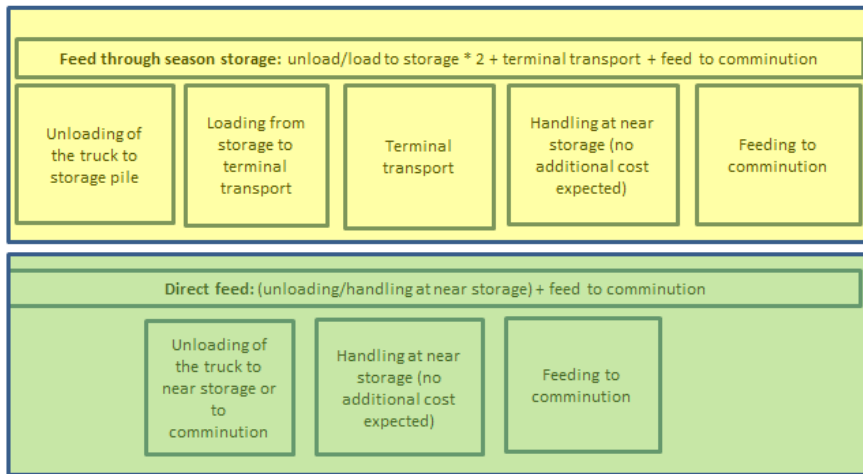


Figure 21. Studied terminal material handling schemes.

The feed through season storage option consists of the following actions: unloading from truck/train to storage, loading from storage, terminal transport, unloading from terminal transport (possibly simultaneously feeding to comminution), handling at near storage (optional) and feeding into comminution. Direct feed consists of the following actions: unloading from truck/train (possibly simultaneously feeding to comminution), handling at near storage (optional) and feed to comminution.

The cost of material handling at near storage was expected to be included in feeding to comminution, based on the argument that avoiding this additional unload-feed operation is the desired option and this can be achieved by optimizing the terminal operations. Additionally, the near storage is managed by the feeding material handling machine and it is very hard to define the situations when a particular grapple load has to be laid down to storage or not.

The main cost drivers for material handling are, density of the material, the size of individual grapple load (cross-section of the grapple opening multiplied by the length of the load) and work rotation (time from collection of the grapple load to release of the load) of the machine. The applied work rotation lengths have been determined in experiments of the handling of pulpwood in terminals. The 60 tonne material handling machine was expected to have a work rotation of 35 seconds for season storage management. The work rotation for the 90 tonne machine was 40 seconds for the feeding of the material to comminution. The respective grapple openings were 1.2 and 2.5 meters. The applied average lengths of grapple loads were 4 meters for uncommercial stem wood, delimbed stem and whole tree and 2 meters for logging residues and stumps. These and applied material density coefficients (Table 4) results in grapple load volumes presented in Table 11.

Table 11. Work rotations (second/work rotation) and applied grapple load sizes in solid-m<sup>3</sup>/grapple load.

	Uncom- mercial stem wood	Delim- bed stem	Who le tree	Stum ps	Log- ging resi- dues	Unit
Material handler, storage	35	35	35	35	35	sec/work rotation
Material handler, feed in	40	40	40	40	40	sec/work rotation
Material handler, storage	3.4	2.4	1.7	0.7	0.9	grapple load, solid-m <sup>3</sup>
Material handler, feed in	4.1	3.0	2.1	0.9	0.7	grapple load, solid-m <sup>3</sup>

A wheel loader was used in the loading of ready-made fuel and for cleaning and other maintenance work in the terminal. The estimated annual hours for the wheel loader were 4300, service lifetime 5.5 years, investment €210 000 and hourly productivity 160 solid-m<sup>3</sup>. The hours of the wheel loader were dedicated to the loading of fuel (3300h) and maintenance and cleaning work in the terminal (1000h). The applied hourly cost was 56.64€/h.

The internal terminal transfers were executed with a special terminal truck. The load capacity of the truck was 90 frame-m<sup>3</sup>. The applied work rotation for the truck was 27 minutes from unloading to unloading. Table 12 summarizes the productivities (solid-m<sup>3</sup>/h<sub>15</sub>) and unit costs (€/solid-m<sup>3</sup>) of handling and terminal transfer machinery for different materials. The presented values represent the technical maximum productivities, assuming that, for example, the comminution machine's capacity does not limit the productivity of the feeding. It is worth mentioning that, for example, the productivity of feeding uncommercial stem wood is 373 solid-m<sup>3</sup>/h, but when the same machine feeds logging residues to comminution, the productivity is limited to 63 solid-m<sup>3</sup>/h due to the more challenging handling properties of logging residues. Two parallel comminution machines were expected for 0.7 and 1 TWh terminals. Based on the presented feeding productivities (compared to comminution productivities) it was assumed that one feeding machine could feed two comminution machines, excluding the feeding of stumps and logging residue. All excess time was expected to be used for near storage management and unloading of arriving trucks and trains.

Table 12. Productivities (solid-m<sup>3</sup>/h<sub>15</sub>) and unit costs (€/solid-m<sup>3</sup>) of handling and terminal transfer machinery for different materials.

	Uncommercial stem wood	Delimbed stem	Whole tree	Stumps	Logging residues	Unit
Material handler, storage	346	247	173	74	90	solid-m <sup>3</sup> /h. 15
Material handler, feed in	373	266	186	80	63	solid-m <sup>3</sup> /h. 15
Terminal truck transport	140	100	70	60	40	solid-m <sup>3</sup> /h. 15
Wheel loader (chips/hog fuel)	160	160	160	160	160	solid-m <sup>3</sup> /h. 15
Feed to crusher €/solid-m <sup>2</sup> (truck)	72	106	33	21	21	solid-m <sup>3</sup> /h. 15
Material handler, storage,	0.4	0.4	0.4	0.5	0.5	€/solid-m <sup>3</sup>
Material handler, feed in	0.5	0.5	0.5	0.7	0.8	€/solid-m <sup>3</sup>
Feed to crusher €/solid-m <sup>2</sup> (truck)	0.9	0.9	1.9	1.4	1.4	€/solid-m <sup>3</sup>
Terminal truck transport	0.5	0.7	1.0	1.2	1.8	€/solid-m <sup>3</sup>
Wheel loader (chips/hog fuel)	0.4	0.4	0.4	0.4	0.4	€/solid-m <sup>3</sup>

### 5.1.5 Measurements

In the smaller 0.3 TWh and 0.1 TWh terminals studied, all measurements were expected to be executed with loader scales (trucks and wheel loader). In the larger terminals 0.7 TWh and 1 TWh, all arriving and departing material was expected to be weighed with a weigh bridge. In addition to this, in larger terminals, a special volume and mass measurement device was expected to be used in connection with comminution, for possible moisture content determination. The applied investment cost of the weigh bridge was €150 000 and the expected investment period was 15 years. The mass and volume measurement device was expected to have an investment cost of €300 000 and a lifetime of 15 years. Figure 22 presents the general cost effect of an individual investment for different terminal output sizes. From the figure, it can be seen that a €300 000 investment incurs a

0.24–0.2 €/MWh additional cost to 0.7 and 1 TWh terminals. The figure highlights the fact that the smaller the terminal is, the more cost sensitive it is when additional investment occurs. For 0.3 and 0.1 TWh terminal the respective additional cost is 0.4 to 1.4 €/MWh.

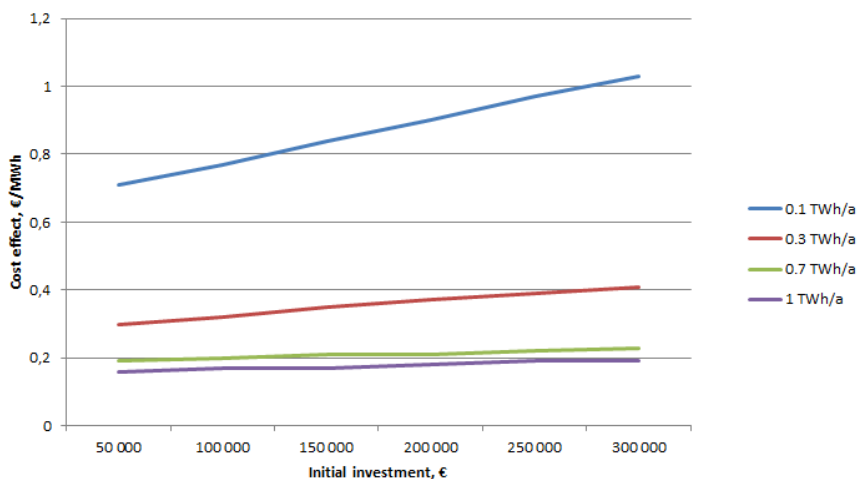


Figure 22. General cost effect of an individual investment for different terminal output sizes.

## 5.2 Cost analysis results: satellite terminal

The following chapters present the results of the cost calculations based on the values presented in the previous calculation method chapter (pages 43–55). The costs are presented for different terminal output sizes (0.1 TWh, 0.3 TWh, 0.7 TWh and 1 TWh) of delivered fuel per year and for different raw fuel materials (uncommercial stem wood, delimbed stem, whole tree, stumps and logging residues).

Comminution with both a stationary chipper and crushing with a mobile crusher was studied for the 0.7 and 1 TWh terminals. Comminution by a mobile crusher was studied for all other terminals. Stationary machinery is applicable only for large terminals (> 0.5 TWh) because of the high investment cost of the unit. A chipper is a good option for all “clean” materials such as uncommercial stem wood, delimbed stem, whole tree and logging residues. However, a chipper is not applicable for material containing soil or stones, such as stump wood. Generally, when applicable, chipping is advantageous because it consumes less energy than crushing.

Crushing is a comminution solution for all solid biomasses. Like chippers, crushers are available both in mobile and stationary units. Here, a mobile crusher was selected because in addition to being a solution for all raw fuel materials, it is a valid option for all terminal output sizes. For this study the selected combination gives a possibility for comparing stationary and mobile machines as well as chipper and crusher technology.

Generally, when stationary and mobile machinery are compared, stationary machinery becomes more economical with large scale use. Similarly, as mentioned, chipping is usually slightly more economical compared to crushing (8–10% lower energy costs, 1–3% lower total comminution costs). In all, the differences are small and the solution that is more beneficial when the whole operation environment (annual output volume, raw material distribution between sources, fuel user requirements) is considered, should be selected as the best fit option.

No natural or artificial drying was considered in the following results. The average cost of the terminal was 15 €/m<sup>2</sup>/year as presented in Figure 20b, with the applied land cost and assumption of the raw material drying from 55% MC to 35% MC the result was slightly more positive for uncommercial stem wood (0.1 €/MWh), zero for delimbed stem and negative for other raw fuel materials (whole tree, stumps and logging residues). Based on this it was assumed that only uncommercial stem wood is stored in season storage. However, for giving comparable values between different raw materials, results are given for all raw fuel materials for all storage and handling options.

### **5.2.1 Comparison of terminal fuel production in chipping and crushing based supply options**

Costs of fuel production by comminution with a full trailer crusher and with a stationary chipper were calculated for 1 and 0.7 TWh terminals. Calculations were executed for both for materials fed directly to comminution without a material storage period in season storage (direct crushing) and for material stored in season storage over a 6 month period (season storage). When total costs for crushing (mobile machinery) and chipping (stationary unit) are compared, chipping with a stationary chipper results in 10 to 13% lower costs compared to a mobile crusher.

Figures 23 and 24 present the costs for direct feed options (chipped/crushed) in 1 and 0.7 TWh terminals. Figures 25 and 26 present the similar values for stored material in 1 and 0.7 TWh terminals. Stump wood is not chipped because it contains impurities that damage the chipper.

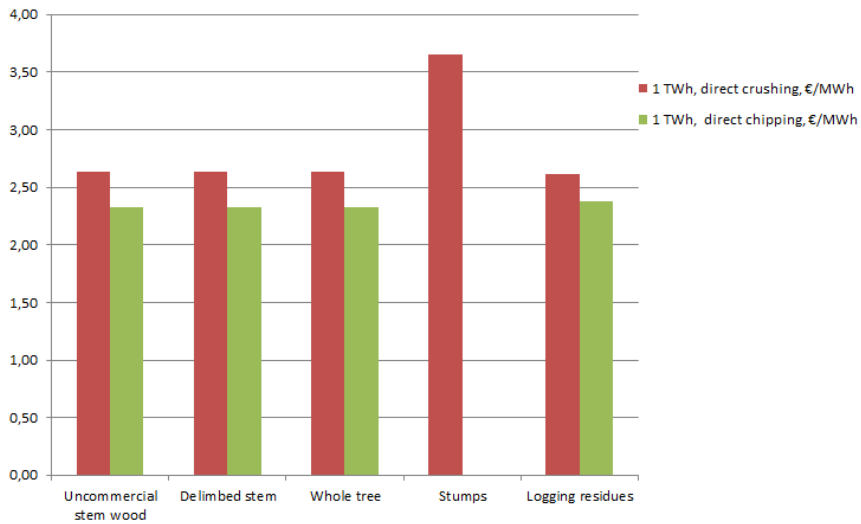


Figure 23. Fuel production costs (€/MWh) in a 1 TWWh terminal with direct material supply to crushing (mobile crusher) or to a stationary chipper.

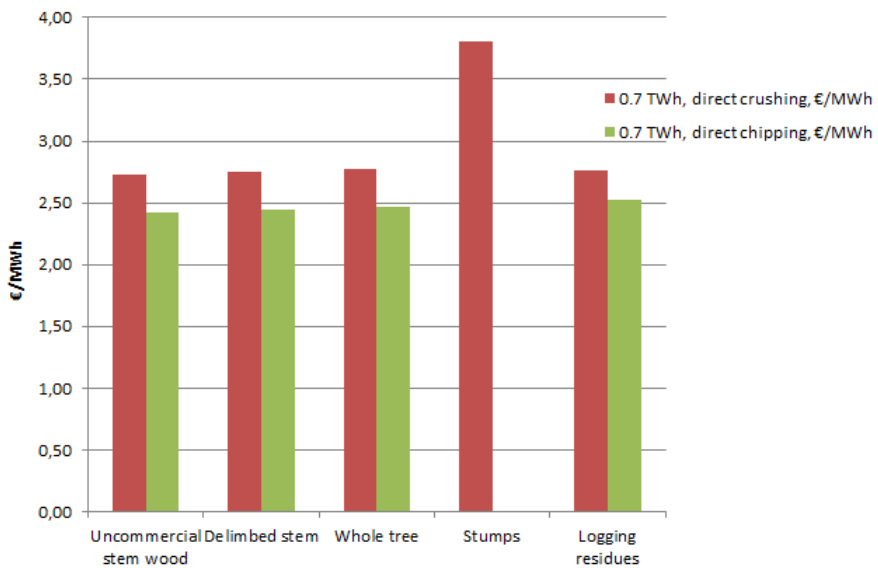


Figure 24. Fuel production costs (€/MWh) in a 0.7 TWWh terminal with direct material supply to crushing (mobile crusher) or to a stationary chipper.



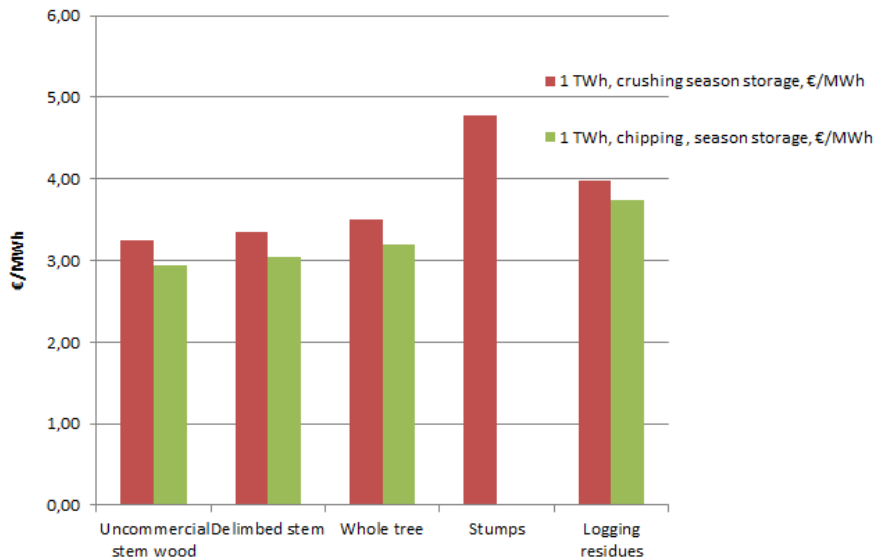


Figure 25. Fuel production costs (€/MWh) in a 1 TWh terminal with material supply through season storage to crushing (mobile crusher) or to a stationary chipper.

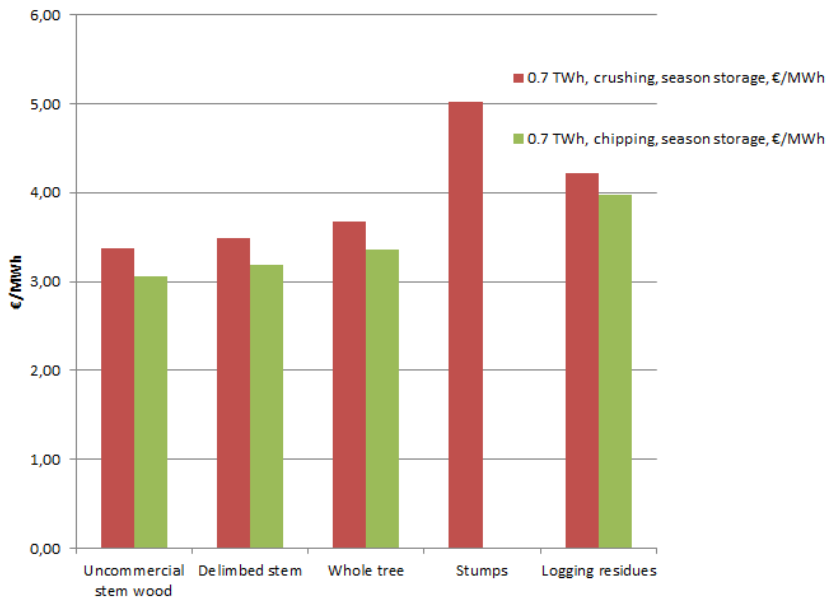


Figure 26. Fuel production costs (€/MWh) in a 0.7 TWh terminal with material supply through season storage to crushing (mobile crusher) or to a stationary chipper.

Figures 23–26 indicate that terminal fuel production based comminution with a large scale stationary chipper is more economical compared to mobile crushing machinery. The overriding reason behind this result is the lower unit cost of comminution with a stationary machine (higher productivity, longer service life of the machine). It is important to note, that a stationary machine is a viable option only for large terminals that provide employment for working the crusher year round (in this case at least 4000 working hours/year). It is also important to note that for reaching the presented cost levels, high utilization rate (> 4000 h/year) must be secured over the whole investment period (15 years). As the investment of a stationary chipper machine is almost four times higher than the mobile crusher, in terms of unit costs the chipper machine is very sensitive to changes in utilization rates.

If a stationary crusher had been selected for comparison, the results would be similar (stationary is more economical on the applied utilization rate) but not exactly at the same level. It is important to note that there are combined chipper-crusher machines available on the market. The operation mode is shifted from chipping to crushing by simply changing the blades and sieves of the machine.

### **5.2.2 Total terminal fuel production costs for all materials in all terminal size classes**

Figure 27 presents the terminal fuel production costs for all materials (uncommercial stem wood, delimbed stem, whole tree, stumps and logging residues) based on the crushing of the material in direct feed and season storage options. Crushing with a mobile crusher was selected for the cost comparison below, because it is a viable option for all materials and all terminal size classes. The stationary chipper is not economical in small terminals (0.3 TWh and 0.1 TWh) and it is not technically applicable for stump wood.

If a chipping option had been studied here, and chipping had been executed with a stationary chipper (in 0.7 TWh and 1 TWh terminals), the results compared against each respective option would be similar, however, cost levels with chipping option would be 10–13% lower. In 0.3 TWh and 0.1 TWh terminals chipping with a mobile chipper would be the reference option. Stumps excluded, the cost with chipping would be 1–4 % lower compared to mobile crushing.

The results indicate that the direct feed fuel supply costs through large terminal units are 21–24% lower in 1 TWh terminal compared to 0.1 terminal. In supply through season storage the respective difference is 19–34%. Also, direct feed is more economical in all size classes (costs are 22 to 78% higher in the storage option), as fewer loading-unloading and terminal transfer sequences are required. Materials with a low density are not well suited for a season storage option as the loading, unloading and terminal transfer costs are high. It can be concluded that

only uncommercial stem wood and delimited stem are viable options for supply that includes long term storing of the material.

When different raw materials are compared against each other the handling cost of stumps stands out. The high cost of stump processing is due to the relatively high handling costs (small grapple loads in loading, unloading and feeding to comminution, see Table 12) and cost of crushing (2.7 to 3.5 €/MWh crushing cost in 1 to 0.1 TWh terminals compared to 1.8 to 2.3 €/MWh of uncommercial delimited stem crushing costs 1 to 0.1 TWh terminals).

The cost benefit of large terminal units accumulates from more efficient storage space use (6m high storage instead of 5m high piles) and higher utilization rate of machines. The use of comminution machinery is especially important in this respect. In large units the machinery use is uninterrupted by transfers from one work site to another, and the machines are fed by purpose built material handlers, with enough capacity to feed even the challenging loose materials efficiently to comminution.

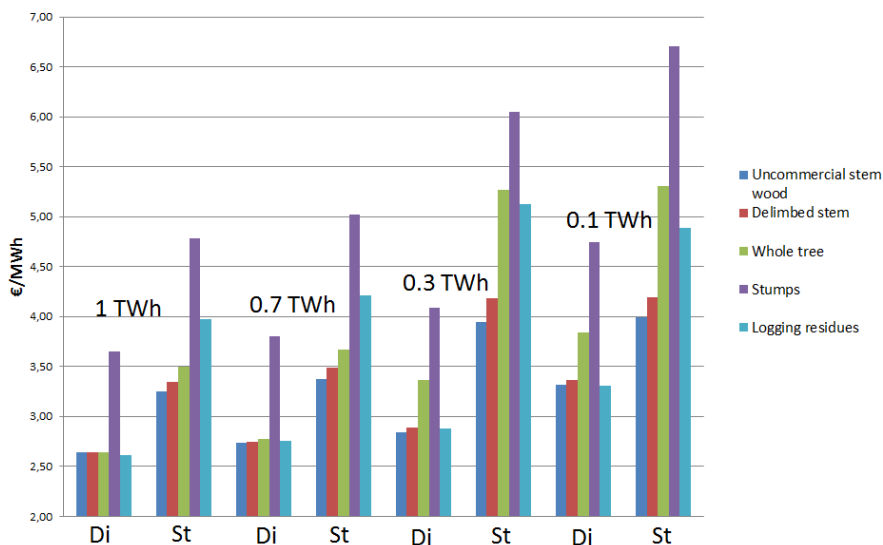


Figure 27. Terminal fuel production costs (€/MWh) in different terminal sizes for all materials (uncommercial stem wood, delimited stem, whole tree, stumps and logging residues) based on crushing of the material in direct feed (Di) and season stored options (St).

In 0.3 and 0.1 terminals feed to comminution is more expensive due to the assumption that trucks are used for feeding of the comminution (see Table 11 for unit costs). Based on the cost analysis, the truck operated feeding is more expensive compared to large scale feeding of the raw fuel material with material han-

dlers. The small annual fuel supply of the two smaller terminals studied does not however enable the economical use of material handling machinery.

### 5.2.3 Breakdown of terminal supply costs

Figure 28 presents the delimited stem cost breakdown (%) in 1 TWh and 0.1 TWh terminals for material fed directly to comminution. In the 1 TWh option the total terminal supply costs are 2.6 €/MWh and in the 0.1 TWh option 3.4 €/MWh. Measurement devices create additional costs for the 1 TWh terminal. However, the lower costs in terminal operations offset the additional cost and in total the fuel production costs are 31% lower in the 1 TWh terminal option.

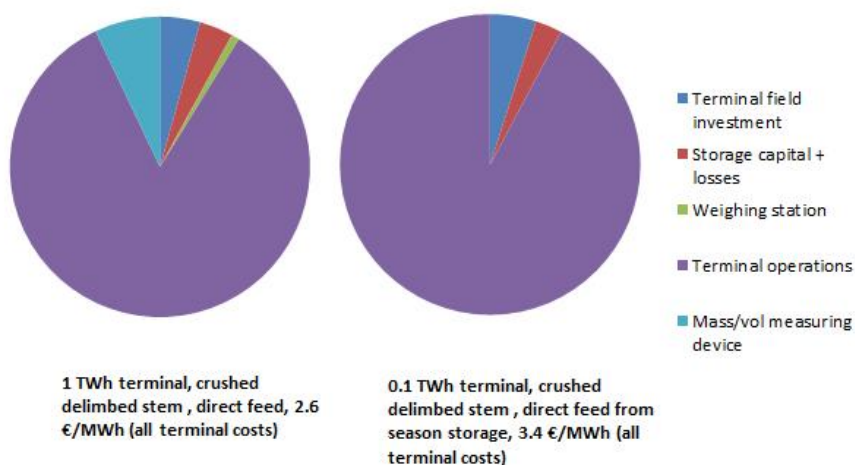


Figure 28. Terminal cost breakdown in percent for delimited stem fed directly to comminution in 1 TWh and 0.1 TWh terminals.

Figure 29 presents the distribution (%) of terminal operation costs for delimited stem in 1 TWh and 0.1 TWh terminals in the direct feed option. The terminal operation costs are 2.2 €/MWh in 1 TWh terminals and 3.1 €/MWh in 0.1 TWh terminals.

The crusher feeding costs are significantly higher in the 0.1 TWh terminal (0.25 to 0.4 €/MWh in the 1 TWh terminal compared to 0.45 to 0.95 €/MWh in the 0.1 TWh terminal). This is mainly explained by the use of trucks in crusher feeding and costs of moving the chipper in the terminal (see Table 11 for exact productivities and unit costs). Additional wheel loader operations are also more costly in the 0.1 TWh terminal. This is due to the fact that a greater terminal area has to be under maintenance per supplied unit of produced fuel. In total the terminal operation costs are 41% lower in the 1 TWh terminal. The main explanation for this is the

lower comminution costs in the larger terminal: 1.8 €/MWh in the 1 TWh terminal versus the 2.3 €/MWh in the 0.1 TWh terminal.

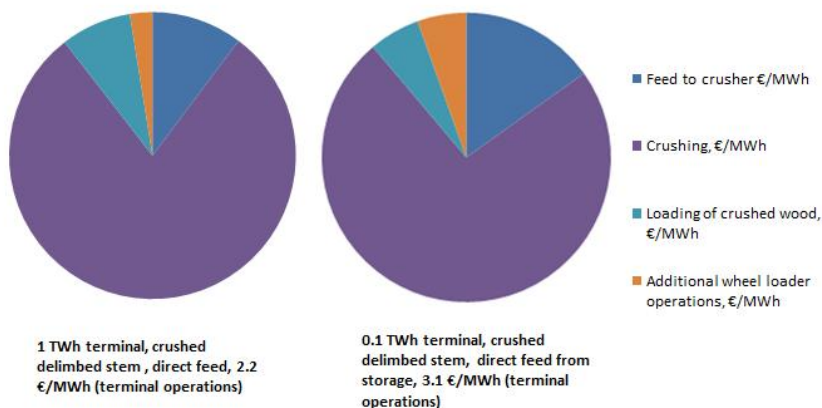


Figure 29. Cost breakdown of terminal operation costs in 1 TWh and 0,1 TWh terminals for delimbbed stem, direct feed to comminution.

#### 5.2.4 Supply cost comparison: direct supply chain and terminal supply chain

Figure 30 summarizes an example of the total supply cost of delimbbed stem in a traditional supply chain and a terminal supply chain. The direct chain consists of the standing wood price, the cost of felling and forwarding, capital costs and costs of chipping and long distance transport (100km truck). The terminal chain consists of the roadside price of wood (similar to standing price + harvesting cost), transport cost to the terminal, terminal costs and long distance transport costs (>600 km, train).

The applied terminal costs are based on fuel supply through a 1 TWh terminal direct feed supply option (2.6 €/MWh) and season storage supply (3.4€/MWh) option. This represents the most economical terminal supply option for delimbbed stem.

The presented cost at plant is 19.6 €/MWh in the direct supply chain and 21.8–22.6 in the terminal supply chain (direct feed/season storage options through a 1 TWh terminal). The figures indicate that fuel supply through a terminal is 12 to 15% more expensive compared to direct fuel supply and 5–9% more expensive compared to the current average price of forest fuel in Finland (20.7 €/MWh, Bioenergia-lehti 04/2014). However, as Figure 25 suggests, the studied terminal supply case is dedicated to long haul (600km by railway) biomass supply from, for example, North-Eastern Finland to a large cogeneration facility located in Finland's Metropolitan area, and thus large scale wood biomass supply can be expected.

With a 50% shorter supply distance (300km) and with an estimated 45% transport cost reduction (applied cost 3.41 €/MWh) the cost of fuel supplied through terminals would be 19–19.8 €/MWh, roughly equal to the supply costs of a direct supply chain.

It is important to note that in the smaller terminals, the terminal costs are significantly higher (up to 34% difference between the total supply costs in a 1 TWh and 0.1 TWh terminal).

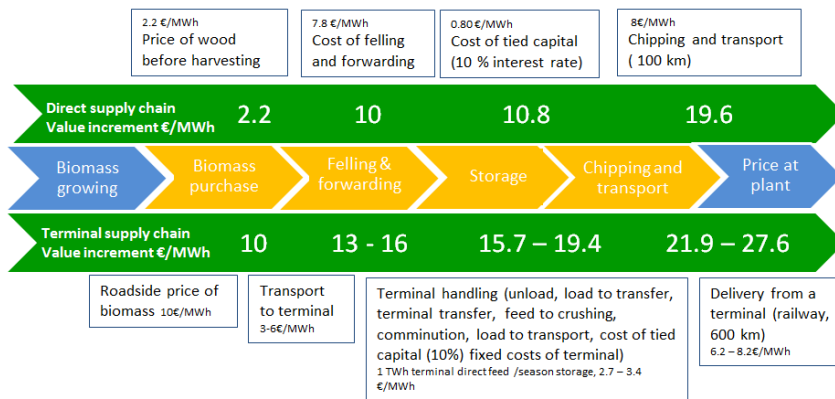


Figure 30. An exemplar summary of the total supply cost of delimbed stem in a traditional supply chain and a terminal supply chain.

## 6. Discussion

The main driver for the introduction of new biomass terminals is the expected increase in the wood fuel use in heat and electricity production from 8 Mm<sup>3</sup> in 2013 to 13.5 Mm<sup>3</sup> by 2020 (TEM 2013). The wood fuel availability (wood fuel balance: availability subtracted by use) is expected to be sufficient for the increased demand (Nivala et al. 2014). However, it is forecasted that especially in the coastal region all available forest fuel must be available in the market for meeting the local forest fuel requirements. This is very seldom the case as the forest owner's willingness to sell wood for energy varies, meaning that the presented potentials for wood availability are not equal to the actual market availability of forest fuels. Thus, the actual availabilities will be smaller and it is likely that regional insufficiency of forest fuel will emerge. Terminals and especially the long distance supply solutions will be the required additional sources for forest fuels.

One key terminal function is the balancing of the fluctuating supply-demand situation of forest fuel business. By widening the forest fuel harvesting season over summer, a more even utilization of machinery and personnel would be possible through filling up terminal storages during the summer season. During the peak load the focus is on the easily accessible terminal storage facilities. This has been the main reason for current terminal investments. Energy companies like Jyväskylä Energia and Rovaniemi Energia have built feed-in terminals to secure their wood supply over challenging seasons and for balancing the overall supply over the course of the year.

Also, as forest fuel use increases, regional availability may exceed forest fuel availability in certain areas of Finland. This creates an unavoidable need for a long haul biomass terminals that can answer to the nationwide procurement challenge by manufacturing and supplying wood fuel from low demand areas to high demand areas within the country.

The previous chapters present examples of fuel supply through terminals with different annual fuel outputs. The presented results are based on certain assumptions on area requirements, on a large number of detailed cost calculation grounds and specific annual fuel flows through different types of storage. The calculations are detailed and give a good indication of the cost effects of different handling

volumes of raw fuel materials. Unfortunately the complexity of real life terminal conditions means that the results cannot be fully generalized, as the operation environment changes from one terminal site to another.

Due to the lack of previous research, especially lack of empirical data and existing points of comparison on biomass fuel supply through terminals, the presented results are theoretical, based on data collected from several individual publications. In real life each terminal is unique and for reaching more accurate cost values, each terminal requires specific case studies and careful planning.

However, the understanding of the cost factors behind terminal supply costs for different materials and different terminal size classes provides an excellent starting point for more case specific studies. Merely understanding the fact that there is no universal terminal cost but instead a cost per each raw fuel material and each machine combination for each terminal size is good starting point for future studies.

The largest studied terminal (1 TWh) and large stationary fuel handling and processing machines were found to be the most cost effective. With the applied cost grounds, for example, high processing volumes and high utilization rates this is evidently true. However, it is likely that the increase in terminal size will not happen overnight, without a break-in and learning period for the terminal operators and without long and secured fuel supply contracts between fuel supplier and users. Also, it is likely that until a large scale operation has been set up, mobile machinery will form the core of the applied machinery in terminals. The higher unit costs of mobile machinery is compensated for by smaller risks for the investor as the mobile machinery can be easily transported from one work site to another. In addition, smaller capital requirement will mean an easier start for the terminal business.

In total, the presented wood fuel supply cost through a terminal (minimum 21.9–22.6 €/MWh) from North-Eastern Finland to the Finnish Metropolitan area (600km railway transport distance) is 5 to 9% higher than the current fuel price paid by users in Finland (20.7 €/MWh). These figures clearly point out that a terminal adds costs to the supply, and that a direct supply chain should be favoured whenever possible. There are however certain benefits that add value to the terminal supply of fuel, the key benefit being the fact that in the Finnish national context wood fuel supply and demand don't match: with presented terminal costs, the effective procurement area is practically the whole country instead of a traditional truck transport based procurement area with roughly a 80 to 150km radius around the user site. The nationwide procurement helps to even out supply/demand differences, creates price stability, and gives access to the best forest stands with good properties for wood fuel harvesting. If a 300km railway transportation cost is applied the supply, the cost of wood fuel via a terminal is 19–19.8 €/MWh, close to the current average price paid by forest fuel users in Finland.



As the procurement and processing actions take place in rural areas, land costs can be expected to be lower compared to more populated urban areas. Work force availability can be expected to be good in rural Finland. The biggest current bottleneck for nationwide forest biomass supply is the lack of railway transport operators; most current transportation methods are bound to the road network instead of economical and environmentally sound railway options. All in all, it can be concluded that the additional cost caused by wood supply through terminals is the price of security of supply.

## 7. Summary

As forest fuel demand increases, new logistical solutions are needed. Most of the increase in use is expected to take place in large heat and power (CHP) production units, which set special requirements for the supply as both procurement volumes and transport distances increase. Biomass fuel terminals broaden the spectrum of available supply options by offering cost effective large scale biomass storage and processing options for securing the fuel supply in all conditions.

This report presents three future terminal concepts: a satellite terminal, a feed-in terminal and a fuel upgrading terminal. The most common current terminal concept, a transshipment terminal, is presented for comparison. There are several transshipment terminals (forest fuel storage and manufacturing sites) in operation in Finland as almost every forest fuel procurement company stores some of its supplied wood fuel in storage sites with good connections to long distance transport routes.

Examples of feed-in terminals (forest fuel storage and manufacturing sites near user sites) can be found for example in terminals owned by energy companies Söderenergi (Södertälje, Sweden), Jyväskylän energia and Rovaniemen energia. Large scale satellite terminal operations (large centralized forest fuel storage and manufacturing sites located remotely from user/users) are being run for example in Stockarydsterminal in Sävsö, Sweden. Fuel upgrading in terminals has so far had a marginal role, except for natural drying of forest raw fuel material during terminal storage.

This report presents the key terminal activities, terminal line-ups as flow charts, terminal area requirements based on terminal output and storage rotations. In addition to this, the report presents a detailed cost analysis on the fuel production costs in the satellite terminal concept with different terminal outputs (0.1, 0.3, 0.7 and 1 TWh) for different raw fuel materials (uncommercial stem wood, delimbed stem, whole tree, stumps and logging residues).

The cost calculation was executed by analyzing material fed to comminution (chipping or crushing) directly from a transport unit (a biomass truck or a train) or feeding of material that has been stored in a terminal and is later comminuted. The storage period increased the costs of produced fuel (by 22% to 78%) due to costs

incurred by the additional load-unload sequences and terminal transport from storage to comminution, and costs of capital tied to storage facilities.

The largest analyzed terminal size class was based on 1 TWh (500 000 solid-m<sup>3</sup>/year), which was found to have the lowest terminal handling and processing costs. For comminution a stationary chipper and a mobile crusher were studied. A stationary chipper was found to be the more economical machine for terminal comminution and the comminution cost with a stationary chipper was 10–13% lower compared to a mobile crusher. A stationary chipper is, however, not suitable for all forest fuel materials like stumps, and in an economic perspective a stationary machine is not fit for the smallest studied terminals (0.1 and 0.3 terminals) so a mobile crusher was selected as the comminution machine for a cost comparison between all studied terminal outputs and forest fuel materials.

The fuel produced in terminals with the lowest terminal costs was forest chips made from logging residues. The cost for logging residue chips with all operational and fixed terminal costs included, fed from a biomass truck and loaded to transport vehicle as chips was 2.37 €/MWh. In the smallest transshipment-type terminal (0.1 TWh) the equivalent terminal costs were 3.31 €/MWh due to the higher comminution costs and higher fixed costs in a smaller terminal. For delimited stems the respective costs were almost equal, 2.33 €/MWh (1 TWh terminal, chipped, direct feed to comminution) and 3.32 €/MWh (0.1 TWh terminal, crushed, direct feed to crusher).

The satellite terminal cost analysis reveals that a large scale terminal can be a cost efficient solution to an over provincial forest biomass procurement challenge. If it is assumed that the cost for delimited stem delivered to a terminal (loaded in a transport vehicle) is 13 €/MWh (standing price + harvesting + transport) and the fuel delivery from a terminal costs 6/MWh (train, 600km), the total cost for fuel delivered from, for example, the Kainuu region to the Finnish Metropolitan area is 21.9 €/MWh to 22.4 €/MWh (delimited stem, 1 TWh, crushing, direct feed 2.6 €/MWh for delimited stem, through storage, crushed 3.4 €/MWh). This cost at the plant is 5–9% higher than the price paid for forest chips in Finland on average in June 2014 (Bioenergia-lehti 04/2014). It has to be noted that the example above refers to a supply situation where wood fuel is transported 600km by railway, whereas the common supply distance for direct supply chains is 80 to 120km.

The figures indicate that terminals do not create direct cost benefits per se: direct supply chains are more economical compared to supply through terminals. However, there are several indirect benefits that can be reached via fuel supply through terminals: regional fuel procurement can be widened to a national scale, security of supply increases (easily available storage facilities), large supply volumes can be delivered by an individual operator, prices remain more stable and a more even quality of delivered fuel can be achieved.

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Author(s)	Matti Virkkunen, Miska Kari, Ville Hankalin & Jaakko Nummelin
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## Solid biomass fuel terminal concepts and a cost analysis of a satellite terminal concept

This report presents three Nordic developing solid biomass fuel terminal concepts: a satellite terminal, a feed-in terminal and a fuel upgrading terminal. The most common current terminal concept, a transshipment terminal, is presented for comparison. There are several transshipment terminals (forest fuel storage and manufacturing sites) in operation in Finland, as almost every forest fuel procurement company stores some of its supplied wood fuel in storage sites with good connections to long-distance transport routes.

This report presents the key terminal activities, terminal line-ups as flow charts, terminal area requirements based on terminal output and storage rotations. In addition to this, the report presents a detailed cost analysis on the fuel production costs in the satellite terminal concept with different terminal outputs (0.1, 0.3, 0.7 and 1 TWh) for different raw fuel materials (uncommercial stem wood, delimbed stem, whole tree, stumps and logging residues).

The satellite terminal cost analysis reveals that a large scale terminal can be a cost efficient solution to an overly provincial forest biomass procurement challenge.

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