GASIFICATION FOR BIO-SNG PRODUCTION ADJACENT TO AN EXISTING FOREST INDUSTRY

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Gasification for bio-SNG production adjacent to an existing forest industry

- A value study on fuel handling and logistics

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Authors' foreword

This work has been performed and co-ordinated by Energiforsk AB in close co-operation with E.ON Gas AB, Swedegas AB and Stora Enso Hylte AB. It was initiated in December 2014 and finalized in June 2015. A reference group has been tied to the project, consisting of the following persons:

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Summary

In order to realize a fossil free vehicle fleet in Sweden in 2030, it is necessary to intensify the biofuel production and that large-scale gasification plants are established. While large research resources have been devoted to ascertain the technical details on the gasification and downstream processing, the interest in logistical issues in terms of both biomass into and the product gas out from the site has until now been much more limited. Meanwhile, the forest industry is in a paradigm shift where newsprint production is in a rapid decline, and whose industries therefore have now begun to show interest in examining complementary businesses. One such possible alternative for the forest industry could be the production of biofuels, since most often the necessary logistics of the raw material already is in place.

The aim of this study is to investigate and analyze added values of co-locating a new large bio-SNG plant with an existing industrial forestry site compared to building it as a stand-alone plant. The focus is on the availability, the logistics and the handling of biomass, and so also the logistics (gas grid vs. flatbed gas transport) of and the available markets for the product gas and the by-products (residual heat, carbon dioxide). A closer study and comparison of six different potential Swedish locations were performed, i.e. Hyltebruk, Värö, Vaggeryd, Braviken, Fors and Norrsundet. The locations were carefully chosen based on the fact that they all today has some sort of existing large-scale forest industry, however, with different conditions regarding logistics for both biomass, gas and residual heat, and the ability to conduct combined and / or alternative profitable business. As a reference stand-alone plant, the bio-SNG plant planned for by EON (the Bio2G-project) has been used. The analysis was carried out with respect to the current situation and what could be expected at the sites in a 10-year perspective.

The results show that several benefits could be gained by co-locating a larger bio-SNG plant at an existing industrial forestry site compared to building it as a stand-alone plant, potentially lowering both the investment and the operation costs. The most decisive parameter was shown to be the availability of low cost biomass in combination with the closeness to a gas grid. Other examples are valuable know-how in large-scale biomass handling, personnel synergy effects in the operation and maintenance and regional needs for new job creations. Based on today´s conditions, Hyltebruk and Värö stands out as frontrunning locations. However, in a 10 year perspective, some of the other sites could also be suitable locations for the current proposal. One such is Vaggeryd, surrounded by forests with excellent growth in combination with the fact that it is situated only 40 km from the national gas grid. Another such is Norrsundet, provided that the regional gas grid Hofors-Sandviken with a connecting LNG terminal in Norrsundet, today under discussion, then is in place. Finally, one common clear challenge for the majority of the studied forestry sites as of today´s situation is the difficulty of finding outlets for the surplus heat. This loss of heat revenue would however be offset by the cheaper cost of biomass.

Sammanfattning

För att Sveriges intention om en fossil-oberoende fordonsflotta år 2030 skall kunna realiseras så krävs att produktionen av biobränsle intensifieras och storskaliga förgasningsanläggningar etableras. Medan stora forskningsresurser har lagts ned på att utröna tekniska detaljer kring själva förgasnings- och efterföljande processteg, har intresset för centrala logistikfrågor vad gäller både biomassa in som gas ut tills nu varit högst begränsat. Samtidigt befinner sig skogsindustrin i ett paradigmskifte där tidningspappersproduktion befinner sig i en mycket snabb nedgång, och vars industrier därför nu har börjat intresse sig för att undersöka kompletterande verksamheter. En möjlig sådan skulle kunna vara produktion av biobränsle, då skogsindustrin många gånger har önskvärd logistik redan på plats.

Denna studie har syftat till att undersöka värdet av en existerande logistik vid etablering av en ny förgasningsanläggning för produktion av bio-SNG vid en befintlig skogsindustri. Studien har sökt, jämfört och analyserat svaren på i första hand fem centrala frågeställningar:

1. Vilka delar av en vedgård ämnad för massaproduktion har ett värde vid etableringen av en förgasningsanläggning baserad på vedråvara och vilket är värdet av en befintlig infrastruktur för mottagning av stora mängder ved?

2. Hur stort är värdet av en befintlig transmissionsledning för gas på en site där en förgasningsanläggning ska byggas relativt att en sådan access inte finns?

3. Vilka potentiella avsättningsmöjligheter finns för den spillvärme som produceras vid sidan av produktgasen i en förgasningsanläggning och/eller vilka avsättningsmöjligheter för värmen bör finnas i närheten för att lönsamhet skall kunna uppnås? Vad är t.ex. värdet av en närliggande pelletsfabrik/sågverk eller annan industri med stort värmebehov relativt om det i dagsläget inte finns?

Med hänsyn taget till ovanstående frågeställningar –

4. Vilka av de studerade variablerna är av störst värde för en lokalisering av en framtida förgasningsanläggning för bio-SNG produktion?

5. Finns det platser i Sverige som skulle kunna vara av intresse att titta närmare på för lokalisering av förgasningsanläggningar för bio-SNG produktion där existerande värden i form av infrastruktur idag redan finns eller är under planering att anläggas inom ett 10-års perspektiv?

Sökande av svaren till dessa frågeställningar har inhämtats via studiebesök, litteraturstudier, kontakter med utrustningsleverantörer samt genom att djupintervjua ett flertal nyckelaktörer inom såväl skogsindustrin som energi- och gasindustrin. För att på bästa sätt kunna undersöka existerande värden i form av befintlig eller kommande infrastruktur med avseende på både biobränsle- och gastransport har man närmare studerat och jämfört 6 olika potentiella lokaliseringar inom Sverige: Hyltebruk, Värö, Vaggeryd, Braviken, Fors and Norrsundet. Lokaliseringarna valdes ut utifrån den bakgrunden att alla idag har eller nyligen har haft någon form av en existerande storskalig skogsindustri, dock skilda förutsättningar vad beträffar logistik/avsättningsmöjligheter för såväl gas som spillvärme, samt möjligheten att

bedriva kombinerad och/eller alternativ lönsam verksamhet. Som referens för en stand-alone anläggning användes i detta fall den 200 MW bio-SNG anläggning som E.ON planerar för (Bio2G-projektet).

Studien pekar ut flera fördelar med att samlokalisera en ny större bio-SNG produktionsanläggning med en existerande skogsindustri jämfört med att bygga den som en s.k. ”stand-alone” anläggning. Dessa fördelar skulle i sin tur med högsta sannolikhet medföra såväl lägre investerings- som driftkostnader. De primära fördelarna som häri identifierats sammanfattas i följande:

- Närheten till skogen, vilket medför kortare transportavstånd och därmed lägre kostnad för biomassaråvaran. Kostnaden för själva transporten utgör ca 30 % eller mer av den totala biomassakostnaden, beroende på fångstradie, vilken typ av råvara och transportslag som används, antal omlastningar som krävs längs vägen in till produktionsanläggningen, m.m. I detta avseende har lokaliseringar som ligger inne i landet en klar fördel, och då särskilt de som ligger i regioner med god skogstillväxt, såsom Vaggeryd och Hyltebruk.

- Tillgång till billiga bi-produkter såsom sågspån och bark som i sin tur kan användas som råvara till bio-SNG produktionen. En sådan tillgång medför en totalt sett lägre råvarukostnad. Värö sticker idag ut i detta avseende, då man där inom kort kommer att ha ett årligt barköverskott på omkring 260-270 000 ton (motsvarar ca 0,4 TWh bio-SNG).

- Mer säker råvarutillgång till följd av att skogsindustrierna antingen ägs eller arbetar i nära samarbete med skogsägare. Detta minskar behovet av större lagringskapacitet och leder troligtvis också till att råvaran i genomsnitt kan köpas in till ett lägre pris.

- Tillgänglig beredd mark för lagerkapacitet och/eller andra aktiviteter som krävs för bio-SNG anläggningen, vilket medför en lägre investeringskostnad vid nyetableringen. Alla undersökta skogsindustrilokaliseringar, förutom Värö, har idag outnyttjad mark, mer eller mindre beredd, i anslutning till befintlig utnyttjad industrimark.

- Logistik för storskalig biomassatransport in till industri redan på plats (lastbil, järnväg och sjöfart), vilket medför såväl lägre investerings- som råvarukostnader. I detta avseende har idag orterna Värö, Braviken och Norrsundet mycket goda förutsättningar.

- Tillgänglig kapacitet i befintlig maskinpark (flis, hugg, kross, tork) till vilken den nya anläggningen kan anpassas, vilket i sin tur sänker investeringskostnaden för bio-SNG-anläggningen.

- Personalsynergier vad gäller skift- och underhållspersonal. Detta minskar det totala behovet av personal på ”site” och därmed också driftkostnaden för bio-SNG anläggningen.

- Möjlighet att göra skogsindustrins transporter ”gröna”.

Resultaten visar också tydligt värdet av att vara ansluten till eller befinna sig i närheten av ett större gasnät. Med andra ord möjligheten att kunna dra nytta av samma fördelar såsom den planerade Bio2G-anläggningen, d v s säker och ekonomisk grön gastransport direkt från produktionsanläggningen till marknaden samt möjligheten till back-up av gas vid tillfälliga driftstopp och uppstart. För att exemplifiera det ekonomiska värdet i siffror kan t.ex. Hyltebruk nämnas. Hyltebruk ligger en knapp km från det nationella gasnätet och har idag möjlighet att transportera grön gas till en total kostnad av ca 50 kr/MWh till en typisk gastankstation (10 GWh/år). Detta är till en betydligt lägre kostnad jämfört med för en bio-SNG anläggning som behöver förlita sig på flaktransport (120-180 SEK/MWh inkl. kostnaden för lagring av gas). Resultaten visar vidare att det till och med kan vara mer ekonomiskt att ansluta platser såsom Vaggeryd, beläget ca 40 km från gasnätet, till det nationella gasnätet, än att förlita sig på flaktransport. En sådan investering skulle kosta runt 300 MSEK; en investering som på årsbasis skulle medföra ca 20 % högre kostnad för gastransporten jämfört med för en site som Hyltebruk.

Studiens resultat visar också att alla de undersökta lokaliseringarna, förutom Vaggeryd, i dagsläget skulle ha svårt att få avsättning för ytterligare spillvärme. Denna förlust av värmeintäkter skulle dock kunna kompenseras genom den billigare råvarukostnaden, och torde således inte vara en nödvändighet för att kunna få en framtida bio-SNG anläggning lönsam.

Bland de variabler som studerats närmare i denna studie pekar resultaten åt kombinationen av tillgång till billig biomassa och närhet till ett större gasnät som den mest värdefulla för en lokalisering av en ny bio-SNG anläggning. Utav de lokaliseringar som närmare häri studerats verkar således Värö och Hyltebruk idag vara de två mest intressanta att titta vidare på. I ett tio-års perspektiv sett kan även andra orter bli lämpliga orter för etablering av en bio-SNG-anläggning. Vaggeryd är ett exempel, omgiven av skog med mycket god tillväxt i kombination med endast 40 km till det nationella gasnätet. Ett annat exempel är Norrsundet. Det pågår idag diskussioner om att ansluta orten till en LNG-terminal och ett nytt regionalt gasnät med sträckan Norrsundet-Sandviken-Hofors. Detta i kombinationen med att orten idag har stort behov av att skapa nya arbetstillfällen, mycket god logistik, stor ”ledig” industrimark samt arbetskraft med värdefull know-how på plats skulle på sikt kunna medföra mycket goda förutsättningar för en ny bio-SNG produktionsanläggning.

List of abbreviations

Bio-DME	Dimethyl Ether originating from biomass
Bio-SNG	Synthetic Natural Gas originating from biomass
CBG	Compressed Biogas (200-250 bar)
CTMP	ChemiThermomechanical pulp
DIP	De-inked pulp
GROT	SWEDISH abbreviation for “GRenar Och Toppar” meaning “Branches and tree tops
LBG	Liquified Biogas
LPG	Liquified Petroleum Gas
m^3 fub	cubic meter under bark
m^3s	cubic meter stacked
TMP	Thermomechanical pulp

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1. Background

In order to realize a fossil independent and a fossil free vehicle fleet in 2030 and 2050, respectively (1, 2), it is necessary to intensify the biofuel production and the realization of large-scale biomass gasification plants. According to the results presented by the investigation on a fossil free transportation sector 2050 (1), it is fully possible, from both an economical and technical viewpoint, to produce around 20 TWh biofuel by 2030, out of which 12-13 TWh would be in the form of biogas, bio-SNG, and bio-DME. Compared to today´s production (1,7 TWh (3)), this is an increase of some 11-12 TWh. Consequently, this indicates that several large biomass gasification plants corresponding to a total production capacity of 7- 8 TWh biofuel must then be in place (1, 4).

Motivated by the different national and international environmental objectives, there is since many years indeed much research and development on-going in the gasification area. This R&D work is in specifically aimed to produce bio-SNG and other biofuels, not least here in Sweden with Göteborg Energi´s GoBiGas project in the frontline (5). The large research resources have been and still are devoted to ascertain the technical details on the various process steps. However, the interest in logistical issues in terms of biomass into and product gas out has been significantly more limited (6-10). Meanwhile, the forest industry is in a paradigm shift where e.g. newsprint production is in a rapid decline. Mills devoted to such production thus have a strong driving force to look for new ways of benefitting from as much as possible of their current equipment and infrastructure. One such possible alternative for the forest industry could be the production of bio-SNG and/or other biofuels. This is so since they very often already have some of the necessary logistics in place.

Historically, the Swedish forest industry has undergone many paradigm shifts that fundamentally have shaken the existing structures. Perhaps the most famous was the great “sulphite death” during the 1960s and 1970s, when the interest in highly specialized and often relatively small scale production of super-alpha pulp as raw material for textile fibers disappeared as a result of a rapidly declining demand and an increased environmental concern. As a result of this paradigm shift, nearly half of Sweden´s production sites for pulp disappeared within a 15 years’ period. However, during this time, the demand for kraft pulp instead rapidly increased and new such mills were established meanwhile existing were largely expanded. Today, with a newsprint production under strong pressure, another paradigm shift is being encountered in the industry. This in turn ultimately means that the forest owners must begin to think about how they could ensure a long-term payment for their wood. During spring 2014, the Finnish forestry group Metsä announced that it has advanced plans for an investment of 10 billion SEK in a biorefinary in Äänekoski, where different materials and most probably also different chemicals and energy products would be manufactured (11). The location Äänekoski is not randomly chosen. On the contrary, it is today the site of an existing large kraft pulp mill. The establishment of a biorefinery at this site would mean that existing infrastructure and logistic systems for the supply of raw materials and perhaps also parts of the existing barking and chipping equipment could be shared. Correspondingly, the Finnish gas transmission system operator/owner (TSO), Gasum, also recently investigated the preconditions for establishing a new gasification plant in the southeastern Finnish town of Joutseno. Today, Joutseno is the home for a large kraft pulp mill. In addition, the Joutseno site is also connected to the national gas grid, which would allow gas produced at the site to reach e.g. Helsinki through the grid.

2. Description of objectives and working approach

2.1. Aims of project

The aim of the current project is to investigate the added value of establishing a new large scale gasification plant at an existing forest industrial site compared to building it in a place with no previous handling and/or logistics of forest resources. More particularly, the study aims to search, compare and analyze the answers to a number of key questions:

1) Which parts of a wood yard (meant for pulp production) have a value in the establishment of a biomass gasification plant and which is the value of an existing infrastructure for receiving large amounts of wood? (Key: The opportunity cost of a "green field" establishment).

2) Which is the value of an existing transmission gas pipeline at a site where a gas plant to be built relative to such access does not exist? (Key: The cost for the new establishment of a gas transmission pipeline).

3) Which potential depositions are available for the waste residual heat from the gasification process and / or which heat depositions are needed in order to achieve profitability? For example, what is the value of a nearby sawmill or other industries with relatively large heat demands relative to a situation when it does not exist? (Key: Estimation of heat production / heat demand in the vicinity)

Finally, taking into account the above issues and key figures:

4) Which of the studied variables / indicators are the most important for determining the location of future gasification plants?

5) Are there places in Sweden, which could be of interest for the location of a gasification unit where existing values in the form of infrastructure today already exist or are being planned to be constructed within next 10 years?

2.2. Delimitations of study

Referring to the project´s budget and timeframe, this study has the following delimitations:

1. Biomass gasification targeted for solely bio-SNG production. The potentials for other bio-fuel production are only discussed very briefly in qualitatively terms.
2. Gasification of solid wood. Fuels such as black liquor and tall oil are not treated in this work, but have been studied elsewhere, see references (6, 7).
3. Large gasification plants (100/200 MW bio-SNG is assumed).
4. No analysis on the best choice for gasification nor downstream processing are included, which process steps are not within the scope of the project.
5. Possible values of existing auxiliary systems such as boilers and/or water cooling systems at the investigated industrial forestry sites are not examined nor discussed.

2.3. Target groups of results and recommendations for utilization

The results of this project are aimed to be utilized by companies considering investing in a biomass gasification facility, and by this study, get a first measure of the value of existing forest industrial sites. In addition, the results could be used by the owners of such sites and facilities in the discussion with a company that has an interest in establishing a new gasification plant. Finally, the results could preferably also be used by municipalities and authorities with an interest in industrial development in traditional industrial areas as well as in the longer term also contribute to increasing production of bio-SNG or other biofuels and thereby reduce the emissions of Sweden's greenhouse gas emissions.

2.4. Description of working approach

The purpose and the objective of this study has primarily been to investigate and analyze the answers to the five central issues described under the heading 2.1. "Aim of project" on the value of management and logistics for the establishment of a new gasification plant at an existing forest industry. The search for answers to these questions has been obtained through field visits, literature studies and by interviewing several key players in both the forest industry, the energy and the gas industry. Furthermore, contacts have been made with equipment suppliers and their infrastructure contractors to obtain cost estimates. This work has subsequently been accompanied by analysis and synthesis work involving estimation and validation by the project defined keys figures. The work was initiated by a visit at Hyltebruk (Stora Enso), where large-scale pulp and paper production is currently conducted. Experience gained during this visit then was used as the basis for the following work. The working approach is schematically illustrated by figure 1.

In order to examine existing values in the form of current and future infrastructure for both biomass fuel and gas transport, a closer study and comparison of six different potential locations for a future large-scale gasification plant has been carried out. The selected sites are Hyltebruk, Värö, Vaggeryd, Braviken, Fors and Norrsundet. For each one of these locations, an over-view analysis, based on the specified key figures, was made. The locations were carefully chosen based on the fact that they all today has or has recently had some sort of existing large-scale forest industry, however, with different conditions regarding logistics for both gas and residual heat, and the ability to conduct combined and / or alternative profitable business. The analysis of the different conditions related to the various locations have been carried out with respect to today's current situation and what is expected to be the case in about 10 years.

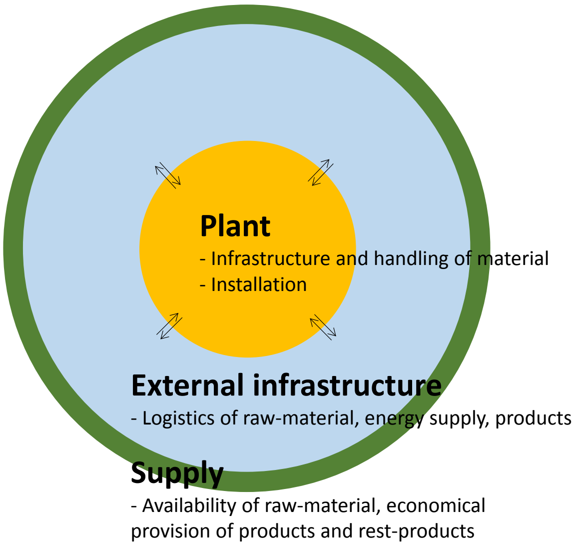

Figure 1. Schematic picture of working approach

3. Description of a bio-SNG plant

A bio-SNG plant and the distribution of its final product is a complex process involving many different steps, from raw material, transport, fuel receiving, pre-treatment, gasification and downstream processing to bio-SNG and finally, its transport to the final user. In order to map out the areas where most synergies can be gained when locating such a plant near an existing forest industry, a starting point from the stand-alone bio-SNG plant planned for by EON (Bio2G-project) is herein taken. This plant is based on a pressurized oxygen blown gasification technology and designed for a production capacity of 200 $MW_{BIO-SNG}$, corresponding to 1,6 TWh bio-SNG on a yearly basis. A schematic flow diagram of the plant is shown in figure 2, showing the steps viewed as part of the process. The unit operations that were identified as important with respect to possible synergetic effects, and thus investigated in this project, are marked by the bright yellow background boxes. Following the description of the selected sites (see ch. 5), the crucial aspects of the different parts identified are described, analyzed and discussed with respect to the specific conditions at each site.

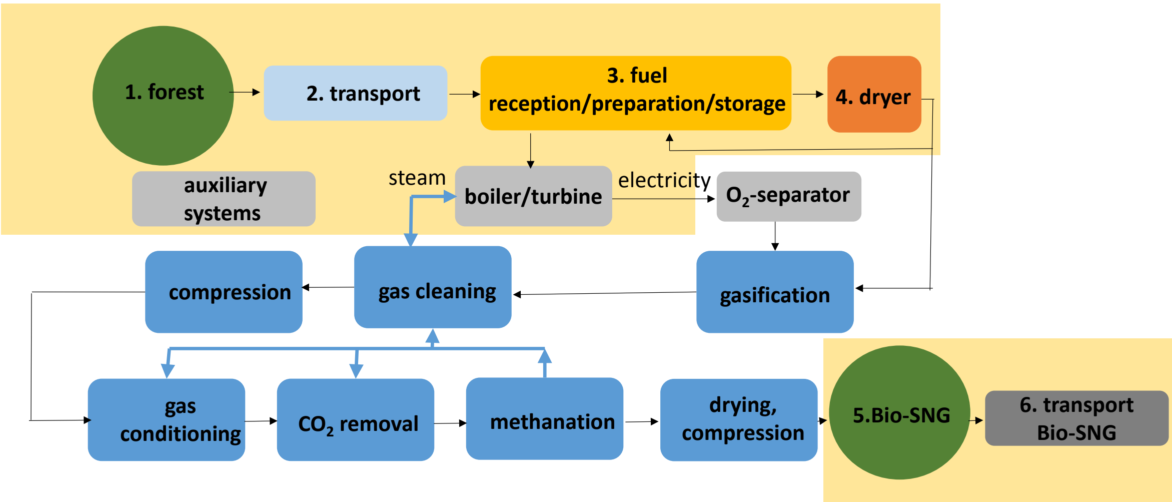

Figure 2. A block flow diagram for a stand-alone bio-SNG plant. The process steps that have been investigated in this project are marked in the bright yellow boxes.

4. Description of Bio2G – a reference stand-alone bio-SNG production plant

In 2007–2008, E.ON started to investigate the possibility to produce bio-SNG from forest residues through thermal gasification and has today far reached plans to build a first-of-its-kind industrial plant for bio-SNG production in Sweden, i.e. the Bio2G-project. However, a decision to proceed with the Bio2G-project cannot be made until Swedish policy instruments for taxation of biofuels, quota obligation and rules regarding vehicles with low carbon emissions beyond 2017 are known. These policy instruments are still investigated by Swedish authorities.

As Bio2G has been used as a reference in this work for establishing a stand-alone bio-SNG plant at a site without any adjacent forest industry, an overviewing description of the plant/project is herein given. This description is focused on those parts that are under investigation in this work, i.e. fuel and product logistics and fuel handling. In addition, a summary of important technical and cost estimations for the plant is given in table 1 (12, 13). These data have in turn been compared and used for estimating the value of existing logistics and fuel handling at the different forest industry sites (described in ch.5). Moreover, the analysis of this work assumes primarily the construction of a facility with a production capacity of ≈ 200 MW bio-SNG. It should be noted, however, that it is fully technically possible, with selected technology, to construct a half as large plant and that depending on the localization conditions, it may also be more strategic to aim for a 100 MW plant. Some pros and cons of building a 200 and a 100 MW facility respectively, is thereof also briefly discussed in ch. 6.9.

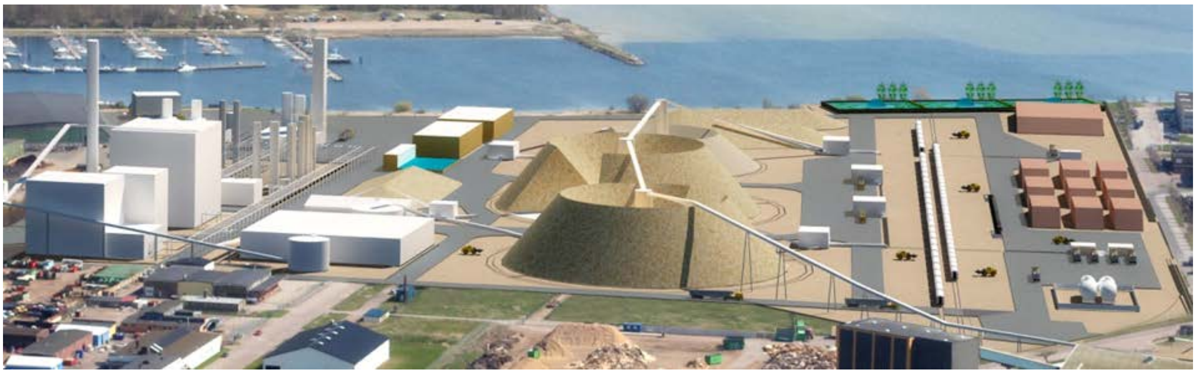

Figure 3. CAD-drawing of the stand-alone Bio2G-plant under planning by E.ON. Source: Picture published and published on the permission by E.ON Gasification AB.

4.1. Location

So far, E.ON has been planning to set up the Bio2G-plant in either Malmö or Landskrona (Skåne/Sweden), motivating this preliminary decision by:

- Transmission gas grid available – The gas grid enables economical long distance transport of the product gas, gas storage and a valuable back-up solution for the supply of gas when the plant is not running at its full capacity.
- Good logistics – Both locations are having excellent access to rail, road and harbour.

  Provision for residual heat – both locations are situated in urban areas with developed district heating systems where the residual heat may be utilised to provide a higher overall energy efficiency.

4.2. Transport of, reception, storage and handling of biomass feed-stock on site

For Bio2G, the plan is to use mainly different types of forest residues as fuel feed stock, such as tops and branches (in Swedish abbreviated as GROT*, grenar och toppar*), pulp and fuel wood, bark, sawdust and stumps, etc. At full capacity, the total fuel supply is estimated to be around 1000 000 tons/yr (wet), corresponding to a fuel input of around 350 MW_{th}.

Biomass will be transferred to the site by road, train and boat. E.ON estimates that about 1/3 of the fuel will be harvested within an 80-90 km distance and transported directly to the site by road. Another third will be delivered via rail, predominantly from the Stockaryd terminal in mid-Småland. One full trainset a night is planned to deliver directly to the Bio2G site. No transshipments of fuel will be required there in between. The remaining third, originating from the northern part of Sweden and/or foreign countries, are expected to be shipped by boat.

Upon arrival to the site, the biomass is expected to have a moisture content of up to 50 wt% and needs to be dried to 10–20 wt% prior to gasification. E.ON estimates that they will need an approximate drying capacity of 20–35 kg/s (based on wet (50 wt%) biomass), depending on which overcapacity they finally decide upon. Besides having capacity for drying all the incoming biomass fuel (350 MW_{th}), the site needs to be equipped with systems for chipping and/or crushing. The feeding system of the gasifier requires chips no larger than 45 mm, and even if a large amount of the total biomass supply can be expected to be fully chipped already on arrival, it is still necessary to have the ability to chip and/or chop biomass quantities corresponding to at least one shipload of for example round wood (≈70 000 ton). E.ON estimates that they will need one line for crushing and two lines for chipping.

In all, extensive logistics and fuel handling systems are needed for a stand-alone industrial bio-SNG plant. This in turn requires a large mill site to be prepared. E.ON has chosen a storage capacity of 500 000 m^3 corresponding to 5–6 weeks of continuous operation, which together with the space needed for the fuel handling, is estimated to result in a footprint of 200 000 m^2, i.e. 80 % of the total footprint of the Bio2G-plant (incl. process).

4.3. Transport of bio-SNG from site

Bio2G will be located in connection to the transmission gas grid and the gas produced on site will therefore be dried and compressed to grid pressure.

4.4. Boiler/turbine and auxiliary systems

Bio2G is planned to be equipped with an auxiliary fluidizing bed boiler with an estimated design capacity of around 40 MW_{th}. The boiler will utilize waste energy streams from the process which together with additional fresh biomass and process steam largely meet the internal energy needs.

District heating is produced partly in the boiler, partly in the process, with a total production capacity of 10–50 MW_{th}, depending on the turbine´s mode of operation (back pressure or condensing mode). E.ON estimates that they will have an utilisation of the produced district heating during around 3000-5000 h/yr.

Cooling water is retrieved from Öresund with a need varying in between 2500–6500 m^3/h depending on the season.

4.5. Manpower

To operate a modern stand-alone 200 MW bio-SNG production plant as Bio2G, around 50 employees are expected to be needed, split between operation and maintenance, excluding fuel logistics. The assumed cost is around 600 000–700 000 SEK/man-year, including taxes and social contributions.

Table 1. Reference data related to Bio2G (12, 13)

Gasification technology	Pressurized oxygen blown gasification, possible suppliers: Andritz Carbona, Foster Wheeler, etc.
Methanation technology	TREMP-type, possible suppliers: Haldor Topsoe, Clariant, etc.
Fuel input	350 MW_{th}, ~2,6 TWh/yr, 1 million ton fuel/yr (up to 50 wt% water content)
Cooling water input	2 500–6 500 m^3/h, season dependent
Bio-SNG (out)	200 MW, ~1.6 TWh/yr
Heat (out)	0–50 MW, ~200 GWh/yr, assuming 4000 h/yr operation)
Electricity (out), to be used internally	16–24 MW
Carbon dioxide (out)	570 000 ton/yr
Fuel	Tops and branches (i.e. GROT), wood chips, stumps, bark and straw, etc.
Wood yard capacity	500 000 m^3, i.e.≈130-150 000 ton
Footprint storage and fuel handling	200 000 m^2
Total plant footprint (land preparation)	250 000 m^2
Total investment cost	≈4 200 MSEK
Biomass cost incl. transport	180–250 SEK/MWh
Installation cost fuel reception (unloading from train, truck and ship, 2 railway tracks, 2 chipping and one crushing line etcetera)	≈430–450 MSEK
Installation cost chipping	≈30 MSEK (2×400 m^3/h)
Installation cost crushing	≈40–90 MSEK
Installation cost dryer	≈80 MSEK (35 kg/s of wet biomass + 30 MSEK (ground and building preparation)
Installation cost wood yard	≈80–90 MSEK
Manpower	Total: 50 persons, out of which 2–3 persons/shift (6 shifts) in the operation

5. Description of selected industrial forestry sites

In the following, an overviewing description of the in this study selected forest industrial sites are given including current activities, production capacities and existing and possible future logistics with respect to both biomass input and bio-SNG output. For clarity, a map is shown in figure 4 with the selected forest industrial sites as well as existing and possible future gas grids marked.

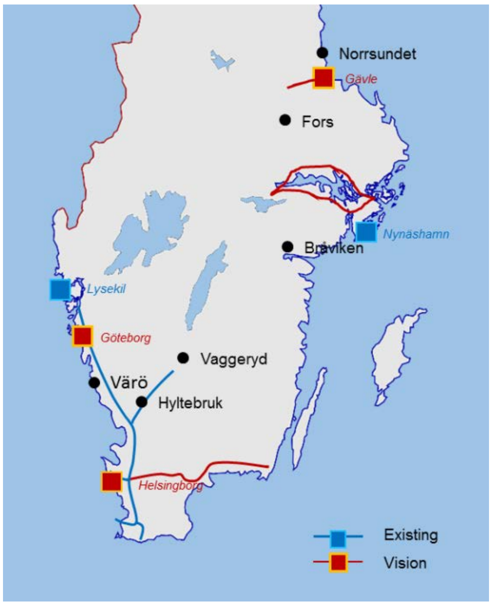

Figure 4. Map of locations studied as well as existing and possible future gas grids and LNG terminals marked. Information about future gas grids were collected from reference 37.

5.1. Description of Hyltebruk (14)

As described in the method section, the integrated pulp and paper mill (Stora Enso) in Hyltebruk is the starting point of our analysis. In order to understand the benefits of placing a gasification plant at the site, instead of building a stand-alone plant elsewhere, we map out the process taking place at Hyltebruk as of today. Thereafter, we identify the critical existing values.

In Hyltebruk (Hyltebruk municipality), Stora Enso runs a large integrated newsprint mill, using thermo-mechanical pulp (TMP) and De-inked pulp (DIP), with an annual production capacity of around 500 000 ton. The mill has a long and successful history. Until the late 1990's magnesium sulfite pulp was also manufactured on the site. In recent years, two newsprint paper machines have been closed down due to a continuous decline in the demand for the paper grade produced. This has meant a 40 % reduction of the production capacity of the mill. Located in-land forest raw materials could be brought to the mill from all directions. Furthermore, the mill lies close the railway line from Värnamo to Halmstad, and is situated less than 1 km from the national transmission gas grid.

The raw biomass material used for the paper production is pulpwood (20%), sawmill chips (35%), and recycled paper (45%). Furthermore, recycled wood is used for production of steam and electricity (130 000 ton/year). Annually, 650 000 ton of raw biomass material is handled at the site. In figure 5, the main flows at the site are visualized, as of today.

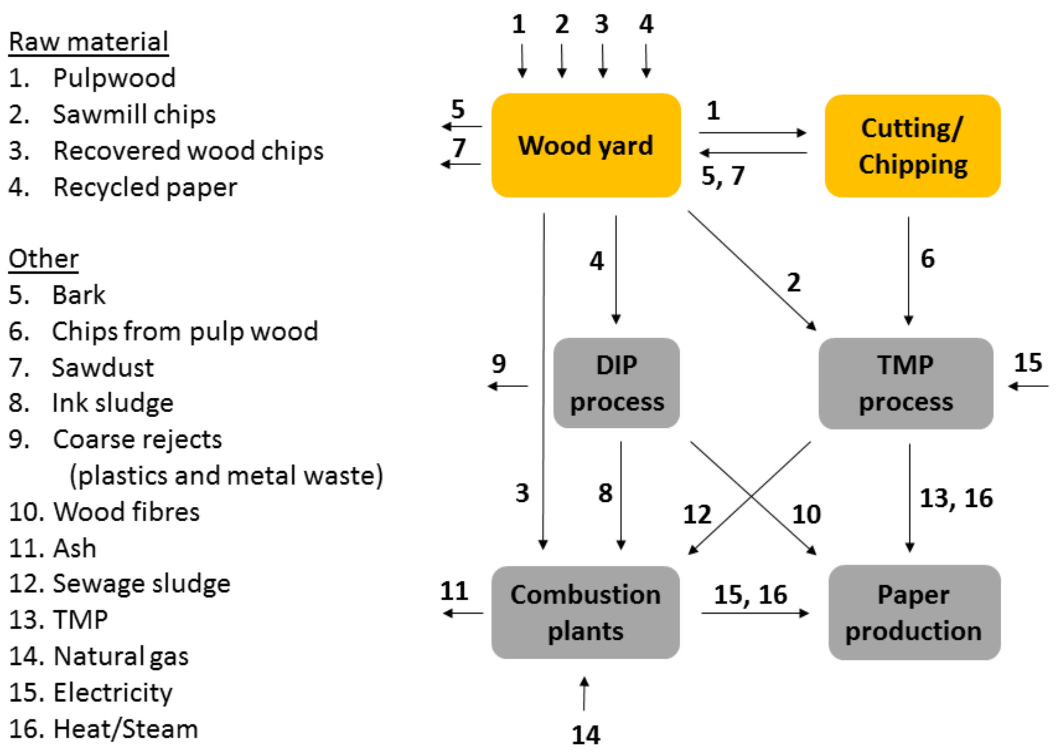

Figure 5. The main energy and material flow at Stora Enso's Hyltebruk site.

The target for the average storage time of the fuel feedstock is 4–5 days, which corresponds to a typical stock of 7 000 ton. The reason behind aiming at such a short storage time is the current secure biomass supply. This has been reached through several years of close cooperation with Sydved and local forest owners, supplying the biomass. Stora Enso today owns 2/3 of Sydved.

The existing wood yard is ~45 000 m^2. A rough estimate made by Stora Enso is that about 50% of the storage capacity is in use. Earlier on, the storage area in use was considerably larger – amounting 70 000 m^2 and the mill has had a biomass fuel storage of 80 GWh once – leaving free capacity in the wood yard and the wood handling area. Several of these areas are still available for storage, and represent also a value if a bio-SNG plant would be built here. According to Stora Enso, additionally 15 000 m^2 of land could be easily accessed. With some further land preparation 5 000 - 10 000 m² is available at the site, accessible for a gasification plant. Other areas adjacent to the mill area could also possibly be available but this would require further municipal planning and land preparation.

The raw material is today mainly transported by road to the site. However, the mill is connected to the national rail network through a branch line to Torup, where the main line from Värnamo to Halmstad is reached. Neither the branch line, nor the main line are electrified. There are even rails leading into the site, but since the strait length of the rails is too short, extra exchange of trains are needed in order to make use of these rails for efficient biomass handling. Furthermore, the placement of the internal rails is on the wrong side of the site, which should demand extra internal logistics. An internal investigation, made by Stora Enso Bioenergy Logistic expert Håkan Alexandersson, showed that today the economic incentives to transport the raw material to the site by railway are limited. This is due to several reasons, the main are: non-electric railway, extensive need for reloading fuel at terminals, no return cargo for the specialised cars, and finally, most of the raw material is available within a relatively short distance. The typical distance of the origin of the raw material is less than 100 km, even though longer transport distances also occur. For example, occasional shiploads are received (via Falkenberg, transported by road to Hyltebruk, 40 km). Accordingly, Stora Enso today does not find it economically motivated to conduct their wood transports to Hyltebruk by rail.

Figure 6. Photo of the railway at Hyltebruk site; today not in use for biomass handling.

20% of the raw material fed into the TMP process is woodchips chipped from pulpwood at the site. Wood chips from nearby sawmills (corresponding to 35% of the raw material) arrives at the site already chipped. Today, only half of the chipping capacity is used, and a chipping capacity equal to 1000 m^3fub/day (corresponding to approx. 5–8 kg/s depending on the water content and the wood dimensions). From chipping, there are two residual products which are not used at the mill; bark and sawdust (50–100 GWh). For paper production, the produced TMP is mixed with fibers, extracted from recycled paper.

Chips of recycled wood is used as fuel in two of the four boilers running at the site. Two bio-fueled powered boilers of 69 and 55 MW thermal effects, and two boilers fired by natural gas of 70 and 20 MW, respectively. The boilers are mainly used to produce steam for the paper process, but also to produce electricity for internal usage, i.e. today corresponding to 7–8 % of the total electricity consumption of the site. The annual usage of natural gas is 30 GWh. The electricity used at the site is mainly used for the TMP process (550 GWh), whereof 300 GWh is recycled as low pressure steam for paper drying. There are up-to-date plans of installing a condensing power plant, increasing the capacity of producing electricity from the excess of low value heat. The plan is to produce a total of 20% of the electricity used at the site internally.

The mill has today a rather large amount of heat excess available (200–300 GWh), but with very limited opportunities for utilisation. Besides the very small portion of excess heat sold to the local district heating network of the community Hyltebruk (19 GWh), there is no nearby industry that today demand the waste heat, and the waste heat is today vented into the atmosphere and the river Nissan, the river splitting the site into two halves. As for the future, it could be speculated that the nearby pellet factory in Kinnared (Derome´s pellet factory situated 12 km from Hyltebruk) and/or the laundry in Torup (Berendsen´s Textil Service AB, 12 km from Hyltebruk) could have an interest of receiving some of the waste heat produced at Hyltebruk, but this in turn would call for an investment in district heating grids to these sites. There are, however, no plans for extending the district heating network of Hyltebruk, neither to Kinnared nor to Torup or any other nearby community.

The Hyltebruk mill today has a total of 410 employees, out of which 170 are working in shifts. The production plant is manned 24-hour/day 365 days/yr by nine persons together with two drivers of the heavy duty loading machines. The shift do not take care of maintenance.

Table 2. Summary of Hyltebruk site

Main product	Newsprint
Annual production capacity	500 000 ton
Annual raw biomass handled at site	650 000 ton
Annual production of by-products	Sawdust and bark (50–100 GWh), low grade heat (200–300 GWh)
Means of biomass transportation applied today	100 % road. Rail access to the site, but not in use. ≈40 km to nearest harbor
Biomass capture radius	≤100 km
Distance to gas grid	≈1 km (national gas grid)
Manpower	410 employees (170 in shifts)

5.2. Description of Värö (15)

In Värö, Södra Cell runs a kraft pulp mill and a saw mill. In 2014 these mills were complemented also by a pellet factory. The company has recently decided to increase the pulp production capacity further from an annual capacity of 425 000 ton to 700 000 ton, making the Värö mill the biggest kraft pulp mill in Sweden alongside with Mönsterås (also owned by Södra). The mill is strategically very well located close to both the forest, the sea and the main (electrified) railway line between Göteborg and Halmstad. Nearby, the Ringhals nuclear power plant is located meaning that also the electrical infrastructure is first class.

The incoming biomass consists entirely of softwood and corresponds to a total intake of around 3 100 000 m^3fub (≈6.2 TWh), out of which 2 100 000 m^3fub is used for the pulp production and the remaining in the saw mill.

The wood yard and the storage capacity at the site is limited, and no expansion plans currently prevail. The latter is derived from the fact that Södra is owned by its members and the forests they in turn own, resulting in a secure biomass supply and a limited need for storages at the site.

The biomass feed-stock is today transported into the site mainly by road (up to 80 % of the total, corresponding at the site to 170 trucks/day), but also by train (2 full system trains /week), with an average capture radius of 120 km from the site. As soon as the planned expansion is complete, Värö states that they will be able to increase the share of rail transport to around 33%. It should hereby be noted that the railway line at Värö mill site is very advantageous reaching all the way into the process and no reloading of the biomass at the site is needed.

There is no available chipping/chopping capacity at the site for parallel activities; all its capacity will be fully used once the expansion of the plant has been completed.

Besides pulp, timber and pellets, the Värö mill produces bark, electricity and heat, respectively. The annual bark production corresponds today to about 540 000 m^3s, i.e. ≈150 000 ton bark incl. 50 wt% water, which after the planned expansion will increase to as much as 970 000 m^3s, thus approximately 270 000 ton. The bark is today primarily used for generating electricity and steam, but also sold as biofuel to external customers. The total return of the latter, however, is poor and Södra searches continuously for new uses for this. Besides bark, the by-product black liquor is available.

Even though the Värö mill is situated in a relatively densely populated area, the external heat utilisation is today limited to district heating delivery to the municipality of Varberg (120 GWh/yr). The potential to increase the hot water supply to nearby municipalities such as Kungsbacka is most probably the double. Today this energy is left out to the sea and the atmosphere.

The site Värö mill has in total 329 employees, out of which 161 persons are working in 6 shifts during 24 hr/day and 365 days/yr. Some of this personnel could, according to Värö, probably, at least in some process parts, be shared with a future bio-SNG plant. In particular, synergy effects could be obtained in terms of the raw materials handling.

Table 3. Summary of Värö site.

Main products	Pulp, timber, pellets
Annual production capacity	425 000 ton (pulp)
Annual raw biomass handled at site	6.2 TWh
Annual production of by-products	Bark (≈150 000 tons), residual heat (≈240 GWh)
Means of biomass transportation applied	road (80%), rail (20%) Connected to harbor
Biomass capture radius	≤120 km
Distance to gas grid	≈10 km (national gas grid)
Manpower	329 employees (161 in shifts)

5.3. Description of Vaggeryd (16)

In Vaggeryd, Waggeryd Cell AB runs a market CTMP pulp mill. The mill makes use of buildings from a kraft pulp mill previously located at the same site and then owned by Munskjö. Today, the annual production is around 150 000 ton, with permission to produce up to 175 000 ton. The company is a subsidiary of ATA Timber AB and use chips from the saw mill business as raw material, originating from mainly spruce and pine. Vaggeryd is a (non-electrified) railway junction with lines to Värnamo, Jönköping and Nässjö. Located inland forest raw materials could be brought to the mill from all directions. The distance to the national gas grid is around 40 km. So far there has been no plans for connecting the mill site to the gas grid.

The annual biomass intake to the site corresponds to 360 000 m^3fub, corresponding to 720 GWh/year. The capture radius for the raw material is limited to around 100 km. Since the majority of sawmills that deliver to Vaggeryd are not located adjacent to a railway, the transport of chips into the site is today exclusively made by road using so called wood chip trucks.

Before the pulp is transported to the customers, it is dried at the site using two LPG powered flash dryers with a total capacity of 12 MW_{th}. The dryers are today used close to their full capacity and considered as a bottle-neck for expanding the production capacity any further. No other heat excess that could be used for the drying is available at the site. Consequently, Waggeryd Cell is today examining the possibility to replace the two LPG fuelled dryers with a bio-boiler. Another theoretical possibility would be to utilize surplus heat from a parallel industrial process, e.g. a bio-SNG plant. Besides the need for pulp drying at Waggeryd Cell, the close-by pellet factory (Neova pellet factory, see reference 17) should be considered as a potential future purchaser of surplus heat. Today, the latter utilize flue gases for their pellet drying, but according to Ingemar Claesson (CTO, Agroenergi Neova Pellets AB), they could still be interested to purchase heat (in the order of 5–20 MW_{th}), if available, for e.g. low temperature drying.

The majority of the produced dried pulp is today exported outside Europe, and its transportation to the customers goes mainly by road (≈3 km), train and finally boat. To those customers that are in Sweden and Europe, the transportation goes most commonly solely by road.

Today, the total foot print of the mill site equals 160 000 m^2, out of which the wood yard is 50 000–80 000 m^2. In addition, Waggeryd Cell owns adjacent zoned land amounting as much as 1000 000 m^2 (i.e. close to 5 times the foot print needed for a 200 MW bio-SNG stand-alone plant), out of which around 470 000 m^2 is today forest area. There are also non-used big buildings from the kraft pulping era that still stands at the site.

Waggeryd Cell has in total 43 employees, out of which 12 are working in shifts 24 h/day 365 days/yr. As for the future, there is no on-going discussions on establishing any new, parallel industrial activities at the site in addition to the development of the existing core business.

Table 4. Summary of Vaggeryd site.

Main product	CTMP pulp
Annual production capacity	150 000 ton
Annual raw biomass input	720 GWh
Annual production of by-products	-
Means of biomass transportation applied	100 % road Approx. 3 km to nearest railway, ≥150 km to harbor
Biomass capture radius	≤100 km
Distance to gas grid	≈40 km (national gas grid)
Manpower	43 employees (12 in shifts)

5.4. Description of Braviken (18)

Sweden's most recently built green field pulp and paper industry is Holmen's integrated TMP and newsprint mill in Braviken north of Norrköping. A saw mill is also included in the mill site. The annual production capacity is 600 000 ton, following the closure in 2013 of one of the mill's three paper machines. Prior to this shutdown, the production capacity peaked 760 000 ton in 2006. The mill is connected with a spur line (non-electrified) to the main (electrified) railway between Norrköping and Stockholm. Almost surrounded by forest the mill is located by the sea with a big and modern harbour. Moreover, the mill currently lacks connection to any district heating network, even if discussions for connecting to the network of Norrköping has taken place. Norrköping is today receiving its district heating from E.ON's biomass- and waste fuelled CHP-plant Händelsöverket.

At Braviken, the pulp was until very recently produced in two separate lines; i.e. one TMP-line using virgin spruce fiber as raw material and one line using recycled paper as raw material. The line using recycled paper was shut down in May 2015, simultaneously as the site proportionally expanded the capacity of the existing TMP production line. This decision is derived from the fact that the mill is forced to cut its newsprint production (now about 30% of the total production capacity) and instead focus on producing paper of finer and shinier quality, i.e., a product highly more demanded on the market than the newsprint.

The biomass intake consists of chips from the saw mill (34 % of total intake) and pulp wood. The pulp wood is debarked and chipped at the site. The maximal debarking and chipping capacity is 130 m^3fub/h (≈30 kg/s), which capacity is today used to about 75 %. Moreover, most of the bark is used as fuel for internal heat and power production, and the site has today a relatively small excess of bark (corresponding to 8.6 GWh/yr) which in turn is sold to external CHP-plants. Besides bark, the boiler (55 MW_{th}) is fed with recycled wood chips, DIP-sludge and dry chips.

All the input biomass is today transported to the mill site by road. Since the saw mill chips is supplied by the adjacent sawmill, the transportation distance is very often limited to 1 km (and never goes beyond 100 km). Furthermore, the product paper is today transported from the site by road, train and by boat. For transportation within the Nordic countries, the transportation is mainly on road, whereas to more far destinations, train and boat is applied.

The wood yard capacity amounts to a foot print area of 60 000 m^2, which under the summer season is in fully use. There is also a storage area for the boiler fuel (bark, dry chips) equal to 22 000 m^2. In addition, the mill owns 100 000 m^2 of land placed within the site, out of which 20 000 m^2 is today leased out.

At the site, a relatively large amount of heat excess is today available. Some of this heat (80 GWh, 125 °C) is annually sold to and used at the nearby saw mill, but the largest part, incl. both high (138 °C) and low grade (50 GWh, 80 °C), is released in Braviken and into the atmosphere. In this case, the high-grade heat origins from the shut-down of the paper machine in 2013 and a notified imbalance in the steam production (2.5 bar (g), 138 °C) during the summer season (55 GWh). However, work is in progress, and Holmen hopes to soon be able to solve this problem by changing the operation profile of the boiler.

There is in total 385 employees at the mill site, out of which around 185 persons are working in shifts (5 shifts) 24 h/day, 365 days/yr. There is currently no on-going discussions on establishing any new industrial activity at the site; the transition to exclusively handle fresh fibers is for the site currently large enough.

Table 5. Summary of Braviken site

Main products	Newsprint, high quality paper, timber
Annual production capacity	600 000 ton
Annual raw biomass handled at site	?
Annual production of by-products	Bark (8.6 GWh), Low grade heat (50 GWh + High-grade heat (80 GWh, sold to the nearby saw mill)
Means of biomass transportation applied	100 % road Connected to railway spur line and harbour
Biomass capture radius	1–100 km
Distance to gas grid	≈250 km (national gas grid)
Manpower	385 employees (185 in shifts)

5.5. Description of Fors (19)

In Fors (Avesta municipality) Stora Enso runs an integrated CTMP and board mill with an annual production capacity of around 410 000 ton board. The mill is located approximately 40 km to the development corridor considered by Swedegas for a possible gas grid investment with steelworks in Hofors and Avesta as the closest large scale industrial neighbours. Fors is located on the main (electrified) railway line between Avesta and Storvik. Located inland forest raw materials could be brought to the mill from all directions.

For the production line, the site mill annually purchase around 450 000 m^3fub (≈ 900 GWh) and another 120 000 ton kraft pulp. In addition, chips are bought to the site (180 MW_{th}) for internal heat and power supply produced in a bio-boiler. The mill is also equipped with an oil-fueled boiler converted to burn wood powder produced from wood pellets. The mill is to over 95% fossil free for its own heat and electricity generation.

The stem wood is chipped at the site, and the chipping capacity is today used to approximately 80–85 % of its full capacity.

The actual capture radius of the biomass depends on the prevailing purchase and harvesting situation, but generally one seek to minimize the transport distances to a capture radius of 70–120 km around the mill site. The mill currently lacks possibilities to use railway for larger amounts of raw material and consequently, all the biomass is today transported into the site by road. It should be noted however that this might change in the near future. According to Magnus Ekberg (Senior Project manager, Stora Enso), there will be, based on economic factors, possibilities to develop raw material rail transportation. The diversion of passing highway opens the possibility to building additional spur line into the production site so that the intake of stem wood can be transported by railway all the way into the site without the necessity to reload. Today, the railway is solely used for transporting ready goods out from the site.

The current wood yard capacity amounts around 25 000 m^3fub, and is in fully use. In addition, the site owns two nearby zone lands covering a foot print area of around 30 000 m^2 (200×150 m^2) which is boarding agricultural and/or forest land, thus a land from a theoretical viewpoint enabling expansion of the current industry and parallel such.

Today, Fors mill has an untapped potential to further use of its waste heat (estimated to <50 MW). To connect to the mill site to the district heating network would cost approximately 80–120 MSEK; an investment too high for realization considering the fact that the Avesta urban area is today supplied with district heating from local waste incineration plant (Magnus Ekberg, Stora Enso).

Referring to the fact that the demand for board is growing globally with 3–4 % annually, the prospects for the Fors mill site are considered relatively good, and there is today no plans for establishing any alternative or additional business at the site. In this respect, it should however be mentioned that the mill has had far reaching plans for using its waste water for biomethane/bio-SNG production by means of anaerobic digestion. An environmental permission is on place for an annual production of 6.3 GWh biogas on site. Still, the company so far has not decided to proceed with this project.

Today, there are 530 employees at the mill site, out of which around 350 is working in shifts for the control and maintenance 24 h/day 365 days/yr.

Table 6. Summary of Fors site.

Main products	TMP pulp, board
Annual production capacity	410 000 ton board
Annual raw biomass handled at site	900 GWh+1.3 TWh (chips)
Annual production of by-products	Low grade heat (≤400 GWh)
Means of biomass transportation applied	100 % road. Connected to railway. ≈ 90 km to harbour
Biomass capture radius	70–120 km
Distance to gas grid	≈450 km (national gas grid)
Manpower	530 employees (350 in shifts)

5.6. Description of Norrsundet (20, 21)

In Norrsundet (Gävle municipality), Stora Enso ran a market kraft pulp mill and a saw mill and pellet production unit, the latter two known as Kopparfors saw mill. The pulp mill was closed in 2009 and the saw and pellet mills in the end of 2011. The annual production capacity of the pulp mill was about 300 000 ton, indicating an annual wood supply of about 600 000 ton dry wood /1200 000 ton wet wood (spruce and pine), thus, in the same order as the total biomass intake planned for Bio2G. The railway line connecting Norrsundet with the main (electrified) line in Hamrångefjärden was upgraded around year 2000. The Swedish Transportation Agency has decided to stop overhauling the line from 2015. Discussions prevail as to how to make use of the mill site, where energy has been in focus. The harbour allows both imports and exports from the site. The Norrsundet village is small with about a thousand inhabitants, making district heating unrealistic.

Today, there is no large-scale industrial activity on-going at the site, and almost all the buildings (besides a larger concrete building) and the machinery (besides a belt dryer (26 MW_{th}) from 2009), originating from the prevailing industrial activities, have been removed. However, the zoned area is large (660 000 m^2) and the site is indeed still excellently situated when it comes to the transport with access to both boat, train and the high-way nearby. Since 2015, the majority of the industrial site is owned by Gästrike Invest and Norrsundets industrifastigheter, which seek for new investors/activities. Recently, a new company called Colabitoil Sweden announced that they will establish a pilot for biodiesel production through hydrogenation of vegetable oil at the mill site, which fully developed, would produce approximately 25 million liters of biodiesel per year.

Other values of this site for establishments of new industrial activities is the availability of staff with good expertise in large-scale production. When the mill site was shut down in 2008, there were 325 employees, out of which the majority was working with control and/or maintenance. It is estimated that a couple of tenth of this personnel is still searching for new job opportunities. Finally, another notable value to consider is the interest of the Swedish TSO Swedegas to establish a regional gas grid between Sandviken and Hofors, connected with Norrsundet with a LNG terminal on site (22). Thus, in all possibly enabling future injection of bio-SNG and large gas customers within reach, fuel gas back-up and so also future export of LBG (liquefied biogas).

Table 7. Summary of Norrsundet site.

Main products	No large industrial activity on-going
Annual production capacity	-
Annual raw biomass handled at site	≈1.2 million ton (2009)
Annual production of by-products	-
Means of biomass transportation applied	Direct access to road, train and harbor
Biomass capture radius	-
Distance to gas grid	≈ 450 km (national gas grid)
Manpower	325 employees (in 2008)

6. Value analysis of critical process steps

Referring to figure 2 (block-diagram), the process steps identified as important with respect to possible synergetic effects based on this work´s purpose and goals are:

1. Biomass feed-stock
2. Transport of biomass material into the site
3. Fuel reception, storage and fuel handling
4. Transport of bio-SNG to the market
5. Market for by-products

In order to understand the costs related to these different process steps, one needs to also understand the underlying crucial factors of each step, which in the following are described and discussed in both qualitative and quantitative terms. This is made from a general view-point, but also from the prevailing conditions of the selected industrial forestry sites outlined in ch. 5 with respect to the key-questions formulated in ch. 2.

6.1. Biomass feed-stock

The most important underlying factor determining the production cost of the bio-SNG is the price of the raw material for the gasification. Forest residues[1], and in particular branches and treetops (GROT), is a biomass material that has been identified as suitable for gasification by several reasons. The most important reason is the relatively low price, see table 8. Another is the potential of an increased outtake of GROT, which mainly will be realized by taking out material that today remains in the forest. This amount, however, is in turn related to and at some point limited by the current withdrawal of stem wood. The average fractionation between stem wood, forest residues (GROT), and stumps depends on the tree species. Typically, the GROT represents 15–35 % of the mass, 45–70 % stem wood and ~20% stumps (4, 24).

[1] Includes here both GROT (In SWEDISH: *grenar och toppar*) and other leftovers from cultivation and harvesting/logging activities (twigs, branches and tops, thinning material, stumps etc.)

Moreover, a critical factor determining both price and availability of forest residues is the forest growth. In Sweden, the forest growth differs significantly depending on the region. In Götaland, the annual forest growth within a radius of 100 km corresponds to in average ~37 TWh, while in Svealand ~30 TWh, southern part of Norrland ~25 TWh, and northern part of Norrland ~11 TWh respectively. This would in Götaland, based on the rough fractionation numbers given above, typically correspond to ~13 TWh (max. potential) as forest residues annually. The corresponding number for Svealand and the southern part of Norrland is ~10 TWh and ~4 TWh, respectively.

Other types of forest residues to consider as fuel feed-stock for bio-SNG/bio-fuel production are secondary residues from wood processing, such as sawdust, bark, black liquor, tall oil etc. Since this study is limited to solid wood material, only the first two is relevant in this work´s value-analysis. As can be seen in table 8, solid by-products can today in average be purchased to a price that is actually lower than the price for other forest residues (e.g. GROT). If these by-products are available at the production site, even lower prices/costs for this fuel feed-stock are to be expected since then also the transportation cost can be rejected (see ch. 6.2-6.3).

Table 8. A list of price examples of various solid biomass material, excluding taxes but including cost for transportation to heat power units or industries. Reference (23).

Fuel type	Price (SEK/MWh)
Densified wood fuels (incl pellet)	282
Forest residues (incl. GROT)	187–195
Recycled/Recovered wood (RT)	90
Solid by-products (incl. saw dust, bark)	164-165

6.2. Transport of biomass material into the site

What primarily determines the choice of transportation of goods is usually by the requirements of quality compared to the cost (25). In this case, the most common quality criteria are punctuality, flexibility, transportation time, security, frequency and reliability. Unfortunately, this is often considered more important than environmental aspects, which often also are ranked lower than the economic aspects. In addition, availability by the different means of transportation is critical.

When it comes to the cost of using the different means of transportation, shipping by boat is by far the least costly. However, shipping by boat always requires reloading, which in turn is a costly procedure. Thus, shipping by boat is usually preferred only on long distances. Next comes rail transportation, but also in this case reloading is often required.

For short distances transportation by road is the first-hand-choice. This is true since the truck could transport the material from and to nearly all locations. In the report “Godstransporter i Sverige” (2012) (25), a minimum distance of 400–700 km was given as a lower limit to when the railway could compete with road transports, but specific examples show that railway may be competitive also for shorter distances, especially when the re-loading could be minimized or even omitted. In the example given in Figure 7 (based on graphs in Johansson and Mortazawi, 2011, reference 26) the critical minimum distance is ~200 km.

In Figure 7, an overview of the cost by road and railway, respectively, is given. The figure is based on data corresponding to figures in Johansson and Mortazawi, 2011 for bundles and chips. The data was converted to cost per energy content assuming that 1 ton corresponds to 3 MWh (wet (non-dried) material (27)). In the study by Johansson and Mortazawi, transportation of branches and tops as bundles by rail is not considered to be a likely alternative and is not included. In the figure, the cost of road transportation of branches and tops, either as bundles or chipped, is shown. In Sweden today, the chipping occurs already at the forest site and transported as chips. In this way, the cost of transportation could be minimized. There is, however, a trend that the residues, instead of being chipped at the forest site (reducing the volume by more than a factor of two compared to the raw untreated material), is transported as is, or in bundles, and chipped at the industrial site of a terminal. This, mainly by economic reasons (28, 29).

In Figure 7, the red dashed line shows the transportation cost by rail – not including any other costs than the transportation as such. However, transportation by rail does include several other unavoidable costs such as transporting the material to and from the tracks, loading and off-loading, rental of containers for chips, etc. The costs for this are included in the dashed blue curve, which thus provides a more realistic image of the transportation costs. At some sites it might be relevant to build tracks into the site. In such a case the second reloading and transportation cost by truck to the site is avoided. The rough costs for each activity used in the estimate are: transportation to tracks ~30 SEK/MWh (with an average distance of 70 km), loading 1.3 SEK/MWh (4 SEK/ton), off-loading 7.3 SEK/MWh (22 SEK/ton), and transport by truck from railway to site (~10 SEK/MWh). The estimation is based on the numbers given in reference (26).

Thus, the major limitation of transportation by rail is the non-flexible infrastructure and the need for reloading and transportation by truck from and to the specific sites (28). In urban areas, another limitation to consider is the fact that the time slots available for a freight train are limited since transportation of people is priority in many areas, as well as reliability (26).

Since the cost of the raw material used for gasification needs to be low, it is crucial to keep the cost of transportation low. When it comes to transportation of biomass for a combined heat and power plant, Nohlgren et al. (30) state that biomass catchment distance must not exceed a radius of 100–150 km, in order to avoid too high transportation costs. That is if the raw material is transported predominately by road. The same critical distances are also valid for a plant producing biofuels (31).Thus, the vicinity of the raw material is indeed an important aspect to consider when selecting the spot for a gasification plant.

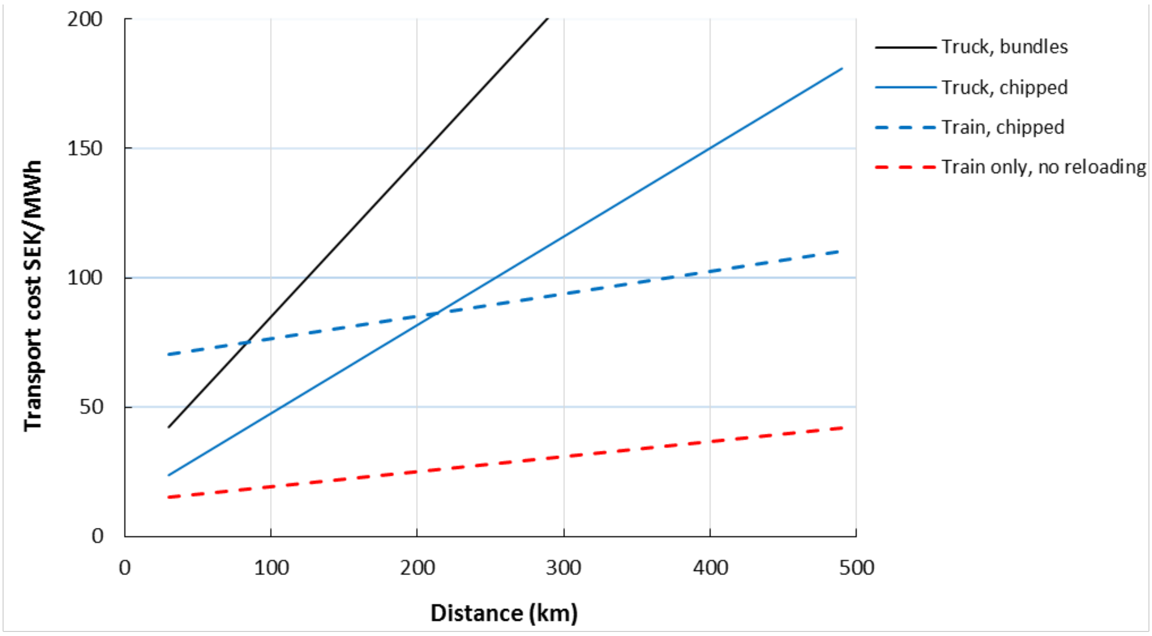

Figure 7. Transportation cost of raw material (here tops and branches), either as bundles of chipped. Graphs are based on the graphs in Johansson and Mortazawi, (26), converted to cost per energy unit using a conversion factor of 3 MWh/ton (with in average 50 wt% water content), Nilsson et al. (27). The relative cost road/rail for chipped raw material holds for all types of chipped material.

6.3. Biomass availability and cost – A value analysis for the selected forestry sites

Vicinity to the forest and access to low cost biomass, such as GROT, are thus important factors when selecting the location for a future gasification plant – either building it as a stand-alone plant or integrating it into an existing industry. Assuming an average transportation distance of 100 km, the transportation cost could constitute to around 30% or more (cf. data in figure 7 with prices for forest residues given in table 8). The longer the transportation distance and the cheaper fuel cost is, the higher this cost share becomes.

When it comes to the vicinity to the forest, this is in particular advantageous for those sites that are located in-land forest enabling biomass transport into the site from all directions. Additional advantage comes with the sites located in Götaland, i.e. the part of Sweden with the highest annual forest growth. Among the selected forestry sites in this study, Vaggeryd is therefore in this respect considered to be the winner, with Hyltebruk and Fors on second place.

As regards the average harvesting radius of biomass, all the studied forest industrial sites state about the same distance, i.e. ≤70–120 km, and the majority of the biomass transports into the site tends today to go by road. For economic reasons, this is the case even for those locations (Hyltebruk, Braviken, Värö) that today have rail access; thus, well in line with the results shown by the graph in Figure 7. Based on this, the value of being connected to the railway seems to be rather low when it comes to the biomass raw material supply as of today. This value may however be completely changed if a bio-SNG plant is co-located with the industrial forest site. First, even though the majority of the studied sites are surrounded by or situated near the forest, supplying a 200 MW bio-SNG unit would likely require a larger harvesting surface area than of today at which rail transport becomes cheaper than road transport, even when reloading is required. Second, one can also expect that the establishment of new railway lines, that permit raw biomass transport without the need for reloading at the site, can more easily be justified when the demand of biomass significantly increases. Based on the cost estimates given in reference (26), savings of as much as ≈17 SEK/MWh biomass supply could be obtained if reloading of biomass could be avoided at the site. Assuming that the latter would apply to at least one third of the required biomass intake for a 200 MW bio-SNG plant, this would then be equivalent to an annual saving of ≥14 MSEK. Consequently, sites such as Värö, Norrsundet and Braviken already today having access to rail enabling large volumes of biomass intake without the need for reloading at site holds definitely a big advantage cf. with the sites that do not have this today. In addition, Värö, Norrsundet and Braviken also all have the advantage of proximity to an industrial harbour.

Another factor that may have an impact on the total biomass cost is the security of biomass supply for a specific site. For example, when co-locating a bio-SNG plant with for example Stora Enso´s site at Hyltebruk, the biomass supply is probably more secured than for a future stand-alone plant such as Bio2G owned by E.ON or other energy companies. The latter is a result of that Stora Enso has a long and close collaboration with Sydved (2/3 of Sydved is owned by Stora Enso) and local forest owners, supplying the biomass. The same applies of course also to Stora Enso´s site Fors, so also to Värö, where the latter is 100% owned by Södra Skogsägarna, i.e. an economic association of forest owners.

Finally, when it comes to estimating and comparing the availability of low cost biomass at the different sites, one needs to also consider possible access to low cost secondary forest residues such as saw dust and bark, which could, as previously stated, indeed result in a clear synergy effect for an adjacent bio-SNG plant. In this respect, Värö is of special interest soon having an annual bark production of as much as ≈250 000–260 000 ton. In rough figures, enough fuel to produce ≈0.4 TWh bio-SNG (assuming 50 % water content (15), 2.4 MWh/ton bark (32), and 60 % efficiency from bark to bio-SNG), thus indeed a significant value to consider. At Värö, there is also black liquor available, which could theoretically also be gasified for biofuel production. This is however, by Värö, not considered as an interesting option as this would, according to the mill, require very high investment costs in combination with significant technical and political risks (15).

6.4. Fuel reception, storage and preparation

Upon reception of the raw biomass material at the site, the following steps are defined as relevant: (i) internal handling (unloading, screening), (ii) storage, and (iii) preparation (e.g. crushing/chipping and drying). At most sites including those in this study, the production capacity has been decreased over recent years. This means that at most sites, the capacity of the forest industrial plants are larger than used today, and for example storage capacity is available for new industrial activities. This means that less investment cost is needed placing the bio-SNG plant at an already existing forest industrial site. The more prepared the available zoned land is, the higher this value becomes. A summary of the total zoned land available at the different selected forest industrial sites as of today is provided in table 9. As can be seen, zoned lands are today available at all locations except for Värö. At the locations Vaggeryd and Norrsundet, respectively, the available land is even several times larger than is actually estimated to be needed for the storage and fuel handling of Bio2G (≈200 000 m^2, 80–90 MSEK, see table 1). The exact value of these existing available land is however difficult to estimate. Most likely, a much smaller foot-print is needed for the co-located bio-SNG plant than the stand-alone plant, mainly justified by safer biomass availability, which means less inventory needs. References (13, 14) appreciate that an additional foot print of solely 50-100 000 m^2 (thus corresponding to a value up to 40-45 MSEK) would be sufficient for the establishment of a new 200 MW bio-SNG plant at an existing industrial forestry site. Less total space than this would mean an increased risk of shortage in the fuel supply.

Table 9. Available zoned land today available at the selected forestry sites.

Forestry site	Available zoned land surface (m^2)
Hyltebruk	60 000 (prepared) + 10 000 (forest area)
Värö	no non-utilized land available
Vaggeryd	530 000 (prepared) + 470 000 (forest area)
Braviken	100 000
Fors	30 000
Norrsundet	660 000

Another value identified by placing a bio-SNG plant at a site already handling solid materials from the forest, is that a practical know-how has been build up at the site during several years of how to handle the raw-materials. This know-how may include everything from water spraying the stacks with water to avoid spontaneous combustion, to how the material is changed during storage, etc. There is also a value in the infrastructure built up at the site, even though this needs to be developed further when increasing the amount (and possibly properties) of the raw material handled. A possible disadvantage with this is that the infrastructure is already build up which might lead to limitations. An example of this is the structure of Stora Enso´s site in Hyltebruk with a river splitting the area of the site in two halves.

To continue with handling and storage of material, a lot of investments in specialized vehicles are already made at the existing forestry sites. Even though a new built bio-SNG plant probably will be fully automated, existing fuel handling equipment is considered as a valuable complement to which the new installations can be adapted, and thereby also cut the investment costs.

An issue worthwhile investigating is whether the handling of material at an already existing site could be automated to the same extent as a new built site. On the other hand, another benefit identified at some sites is that existing staff may partly also handle the bio-SNG plant. In particular, synergy effects are to be expected in the covering of occasional situations and interruptions in the automation, so also in the raw biomass handling. This may to some extent cut the operation costs of the bio-SNG plant (600 000–700 000 SEK/man-year, see table 1).

When it comes to preparing the material, process steps such as screening, crushing, chipping and drying are of consideration. For Bio2G, the fuel portfolio is based mainly on fuel wood, forest residues (branches and tops), pulp wood, bark, and potentially straw. One possible value identified by placing the bio-SNG plant at an existing forestry site is if capacity is available at a chipper/crusher already in use, potentially saving investment costs, so also maintenance costs. The latter supposes, however, that the existing forest industry has about the same specification in terms of chip size as requested by the gasification process. If not, the holder of such capacity available does not contribute with any value for an adjacent bio-SNG establishment. As described in ch. 5, there is some chipping capacity available at some of the selected locations; i.e. Hyltebruk (5–8 kg/s), Fors (2–3 kg/s), Braviken (7 kg/s). Based on the estimated chipping capacity needed for a larger bio-SNG plant (in the range of 100 kg/s) and what investing cost of such is in relation to the total investment cost (≤1 %), the values of the available chipping capacities at the selected forestry sites are herein assessed to be small, up to 5-10 MSEK (13,14). Depending on the type of feed-stock mixture available at the specific site, these existing chipping capacities could either work as “free” capacity to which the new installations can be adapted or utilized as valuable back-up solutions in the event of malfunctions of the new ones.

Furthermore, as regard dryer installations, it appears to be only Norrsundet out of the selected forestry sites that has a dryer available that could potentially be used in a bio-SNG plant, i.e. in this case a belt dryer of a capacity of 26 MW_{th} from 2009. As this dryer is quite modern, it would appear reasonable to assume that it is possible to upgrade this to the capacity of the Bio2G demand, i.e. 40 MW_{th}, which related cost is expected to be significantly less than purchasing and installing a complementary new dryer. According to references (33–34), it should be fair to estimate the value for the existing 26 MW_{th} dryer to around 25–35 % of the installation cost for the new 40 MW_{th}, i.e. 20–25 MSEK. Further value comes to if one also takes into account the cost of the land and building preparation needed for a new drying installation (i.e. 30 MSEK, see table 1).

6.5. Transport of Bio-SNG from the site to the market

In all, three different methods for gas transport are in principle available in Sweden today. These are gas grid transport, either by the national or a regional/local gas grid, and transport in compressed form by road in mobile storage units, either in compressed or liquefied state. Among these, gas grid transport is the most secure, energy efficient and environmentally friendly option (35).

6.5.1. Gas grid transport

The Swedish national gas grid for natural gas is limited to the very southwest of Sweden and extends from Klagshamn to Stenungsund, i.e. situated 50 km north of Gothenburg, with a detour to Gnosjö in Småland, see figure 4. The gas network is made up of a transmission network with high pressure (30–80 bar), distribution and service pipelines (4–10 bar and 100 mbar), and a number of measuring and regulating stations (MR stations) where the pressure is reduced.

In addition to the national gas grid, there are a number of regional and local gas grids in Sweden, e.g. the old town gas grid in Stockholm and the gas grids in Örebro, Kristianstad, Linköping and Visby, etc. There is also lots of interest for the construction of new regional gas grids to be connected to a liquefied natural gas (LNG) harbour and supplied with bio-SNG from regional bio-SNG producers. Regions of special interest for the establishment of regional grids are today Mälardalen (36), Hofors–Sandviken-Norrsundet (22, 37), and Klippan–Kristianstad (37), respectively, and feasibility studies for these regions are on-going. The first two grids mentioned, i.e. the one in Mälardalen and the one connected to Norrsundet, are of special interest to consider in this work as these could open up for bio-SNG injection, grid transport and gas markets from potential future bio-SNG plants to be located at Braviken, Fors and/or Norrsundet, respectively.

For an industry today connected to the transmission gas grid, the total gas cost (including transport) is in the range 20–40 SEK/MWh gas, depending on the purchased gas amount. For those industrial customers that instead are connected to the distribution grid, the equivalent cost ranges from 40–90 SEK/MWh gas (22, 37).

6.5.2. Gas transport by road

When no gas grid is available, gas transport by road in mobile storages is the remaining alternative, either in liquified (LBG) or compressed form (CBG, 200–250 bar), where the latter is by far the most common gas transport alternative in Sweden today.

The general advantage of CBG-transport, besides the flexibility, is that there are plenty of trucks on the market and that investment to get started with the actual gas transportation at a bio-SNG production site is relatively low. However, in contrast to the gas grid transport, the road transport increases linearly with the transport distance. Other critical issues to consider is also the need and additional cost for further gas compression (from 60–70 bar to 200–250 bar), so also the necessity and cost for gas storage at the production site or at the gas filling station. The average cost for CBG-transport in Sweden is in the range of 80–140 SEK/MWh, in this case including the cost for compression, an average transport distance of 100 km, but assuming no need for any gas storage at any site (38). As illustrated in figure 8, it seems as CBG transport can never be economically motivated over grid transport unless the gas demand of the industrial customer is ≤10 GWh/yr in combination with that the gas transport distance can be kept less than 100 km and/or if no gas grid is available sufficiently close-by the production site. It is worth noting however that the given CBG-transport costs in figure 8 are related to CBG transport by conventional flatbeds made of steel (2 full flatbeds/CBG-transport). If one instead would have applied data for light weight flatbeds made of new composite materials, this cost would most probably been less (35). To exemplify, E.On Gas Sverige AB (13) states that at longer distances (> 150 km), the operation cost for gas transportation with steel flatbeds can be up to 3 times more expensive than with composite flatbeds. The latter, however, at the expense of a higher investment cost. Finally, as a comparison to gas grid and CBG-transport, LBG-transport has also been included in the figure 8 (35), which could for large gas production volumes in combination with long gas transport distances be an interesting alternative.

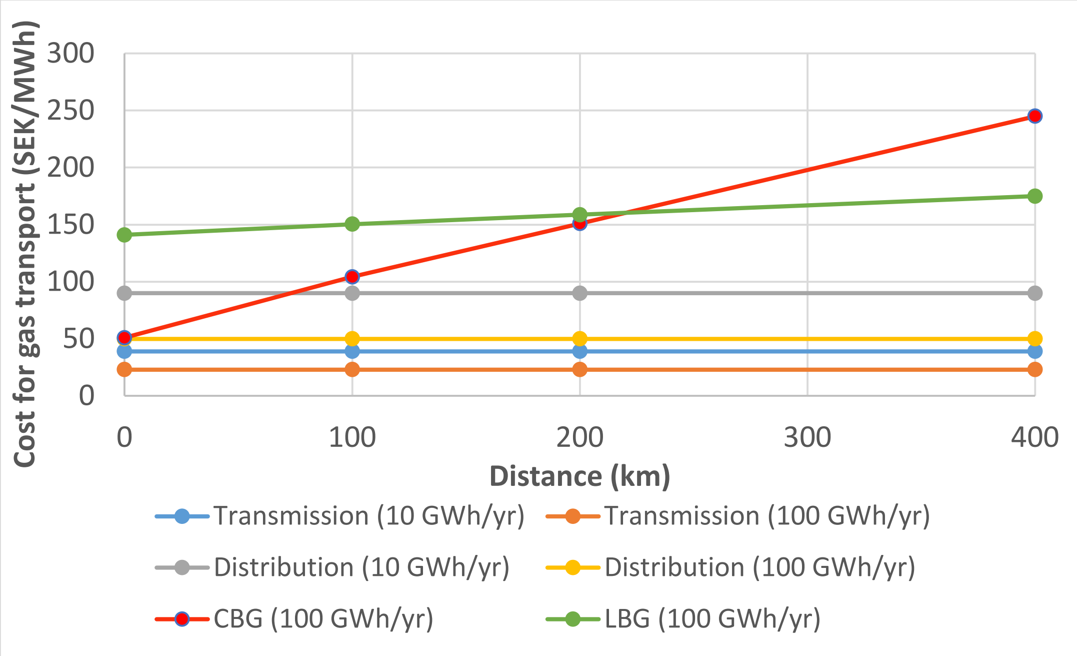

Figure 8. Cost comparison (SEK/MWh) vs. transport distance (km) for different bio-SNG transport alternatives. Given costs for the different grid transport alternatives are from references (37, 38), whereas the given costs for CBG and LBG-transport are from reference (35). The given cost estimates for CBG-transport includes, besides the transportation costs, the cost for compression (up to 200 bar) and the cost for the utilized flatbeds, assuming 2 flatbeds in steel/CBG-transport which are completely emptied at the disposal site.

6.6. Gas grid transport or CBG transport – A value analysis for the different locations

Today, the selected locations in this study have substantially different conditions in terms of opportunities to larger volumes of bio-SNG transportation. In this sense, Hyltebruk is the frontrunner location, located less than 1 km to the national gas grid, with Värö in second place with just over 9 km. How much is this proximity to the national gas grid worth at a future establishment of a bio-SNG plant in comparison to a location that is much further away and which instead must rely on flat-bed gas transportation? As an attempt to answering this question, cost estimations for connecting future bio-SNG plants to the existing national gas grid were made for those locations that today are situated sufficiently near the grid for new pipeline facilities shall be realistically feasible alternatives, i.e. Hyltebruk, Värö and Vaggeryd. To get a sense of how the amount of injected gas affects this cost, calculations have been made for both a 100 MW and a 200 MW production unit, respectively. For the other locations investigated, i.e. Braviken, Fors and Norrsundet, distances to possible future regional gas grids are instead given and from these, approximate costs were estimated. In these cost estimates, it was assumed that the connecting industry (i.e. the bio-SNG plant) has accounted for the entire investment cost at the start-up, meaning, with prevailing conditions (22), that no injection fee is being charged. More specifically, the estimated investment cost for establishment of a new gas connection includes in this case cost estimates for the purchase, transport and installation of a pipe-line (in steel, designed for 80 bars), the mechanical work including testing and the connection itself. Finally, it was assumed that the gasification plants would deliver the gas at high pressure (i.e. 55–60 bar) and that no further compression would be required. The results are summarized in table 10. As expected, the cost for the new pipe-line establishment increases with the distance to the existing transmission grid. The latter function is however not linear; economy of scale works also for longer distances such as to Vaggeryd allowing that the indicated cost uncertainty of –20 % is more likely in this case compared to the other two (22). It is also evident from this table that it is only a minor difference in cost when increasing the gas injection volume by a factor of two, i.e. thus going from a 100 MW to a 200 MW plant.

In order to give an idea how the estimated investment costs given in table 10 would impact the total cost for gas grid transport (i.e. investment cost for new pipe-line + operation cost for gas grid transport), the investment costs given for 200 MW for the different locations in table 11 were translated into annual costs by using the annuity equation:

$$k = p/[1-(1+p)^{-n}] \qquad \text{(Eq. 1)}$$

where k is the annuity factor, p is the discount rate and n is the life-time of the plant. The annual investment cost is then obtained by multiplying the annuity factor with the total investment cost, according to:

$$\text{annual investment cost} = k \times \text{total investment cost} \qquad \text{(Eq. 2)}$$

In this study, p was set to 8 % and n to 20 years (12), respectively, where n in this case refers to the life-time of the bio-SNG plant, which together gives an annuity factor equal to 0,10. The results obtained for two different but in Sweden today typical gas customers connected to the distribution grids are displayed in table 5, i.e. a customer purchasing ≤ 10 GWh/yr (e.g. a vehicle gas station) and another customer purchasing ≤ 100 GWh/yr (e.g. a medium sized industry). For a site such as Hyltebruk, situated less than 1 km from the gas grid, it can be concluded that the additional annual cost for this new pipe-line investment adds less than 1 % to the total gas transport cost, thus, a cost that can be considered as close to insignificant.

For sites such as Värö, located about 10 km from the gas grid, the total gas grid transportation ends up at costs of 55 and 95 SEK/MWh for a 100 and a 10 GWh gas/yr customer, respectively. Thus, an additional cost of 5 SEK/MWh compared to when the gas connection is already in place at the bio-SNG production site. For locations such as Vaggeryd situated as far as 40 km from the nearest gas grid, the equivalent cost is 70 and 110 SEK/MWh, thus an additional cost of 20 SEK/MWh related to the cost of the new pipe-line investment, whereas for Braviken, under the assumption that the regional grid under discussion in Mälardalen is on place, ends up at the costs 130 and 170 SEK/MWh, respectively.

For comparing these costs with flatbed gas transport on road, one needs to compare with not only the cost for the transportation itself (80–140 SEK/MWh), but also to include the additional cost for gas storage at the production site. The installation for a conventional gas storage at 200–250 bars is very costly, i.e. 43 SEK/kWh (39), and the critical issue in this case is therefore how much gas you need to store, which in turn is dependent on both the bio-SNG plant´s supply security, the demand for gas in the vicinity and the logistics. As regards the gas market, it would appear reasonable to assume that this will not be a limiting factor as both the transportation and the shipping sector are aiming to switch into non-fossil fuels within a few decades and that their needs by far would exceed the current production volume of ≈1.6 TWh bio-SNG. Moreover, the logistics regarding the flatbed transport itself should also be fully possible. An annual production volume of 1.6 TWh corresponds roughly to 30 trucks/day (assuming 13 000 Nm^3 gas/load), which compared with the logistics conducted on a standard-sized pulp mill today is relatively moderate. Consequently, it seems to be reasonable to estimate the needed gas storage volume based on the plant´s security of supply. According to reference (40), a storage of only 2–3 days should in this case be sufficient. Assuming 3 days, this corresponds to a gas volume storage of approximately 1.3 MNm^3 and an annual investment cost of 36 SEK/MWh, calculated from Eq. 1–2 assuming p=8 % and n=20 years, thus the same assumptions made when estimating the annual investment costs for the establishment of new gas grids. Adding this specific cost for gas storage to the flatbed transportation cost (80–140 SEK/MWh), it could be concluded that the alternative cost for gas transportation by road (116–176 SEK/MWh) becomes significantly more expensive than connecting forest industrial sites such as Hyltebruk, Värö and even Vaggeryd to the gas grid. This is so even though the actual storage capacity is relatively small. Similar conclusion should be reasonable to draw also for sites like Norrsundet and Fors in the future, provided that the regional gas grid connected to Norrsundet by then is a reality. It could further be concluded that it does not seem to be cost realistic to establish a large bio-SNG plant at a site, without connection to a gas grid, relying solely on CBG-transport on road and/or if the distance is as far. If the latter is the case, LBG-transport by road or the production of other biofuels, e.g. bio-alcohols, should instead be considered. Another option to consider is gas transport, either as CBG or LBG, by rail; not yet applied in Sweden, but, in the form of LNG, since the early 1970´s in for example Japan (41).

Table 10. Estimated investment costs for connecting different locations to the gas grid (22). For Hyltebruk, Värö and Vaggeryd, the given distance refers to the existing transmission grid, whereas for Norrsundet, Fors and Braviken, the distance refers to the estimated distance to the nearest future regional gas grid; today under discussion.

Location	Distance plant – gas grid (km)	MSEK (–20+50 %) – 100 MW	MSEK (–20+50 %) – 200 MW
Hyltebruk	0,7	6	7
Värö	9	65	73
Vaggeryd	41	280	315
Braviken	≈170	Ca 4×Vaggeryd	Ca 4×Vaggeryd
Fors	≈40–50	Similar to Vaggeryd	Similar to Vaggeryd
Norrsundet	≈0 – 1	Similar to Hyltebruk	Similar to Hyltebruk

Table 11. Estimated total costs ($Distr_{tot}$, given in SEK/MWh bio-SNG) including the annual investment cost for connecting the different locations to the gas grid (annual inv.) + the cost for gas transport to customers connected to the distribution gas grid (Distr.) purchasing typically 10 and 100 GWh/yr, respectively. The gas injection point is assumed to be into the transmission grid. The annual investment cost was calculated by eq. 1–2, using p=8 %, n=20 years.

SEK/MWh	Hyltebruk	Värö	Vaggeryd	Braviken	Fors	Norrsundet
annual inv.	0,4	5	20	80	Similar to Vaggeryd	Similar to Hyltebruk
Distr. 100/10 GWh/yr	50 /90	50/90	50/90	50/90	50/90	50/90
$Distr_{tot}$ 100/10 GWh/yr	50/90	55/95	70/110	130/170	Similar to Vaggeryd	Similar to Hyltebruk

6.7. Market of by-products

In order to achieve as good profitability as possible with a bio-SNG plant, it is highly preferable to have a market not only for the main product biofuel, in this case bio-SNG, but also for the main by-products electricity and residual heat. The demand of these by-products is evidently very much dependent on the actual location of the plant. As described in section 4, the Bio2G plant is chosen to be located close to the market with respect to both bio-SNG and heat since the locations under consideration (Malmö/Landskrona) have connection to both the gas transmission grid and larger district heating systems. There is also an available market for electricity surplus, but this would in this case not be utilized since this electricity would be fully needed for the internal processes. E.ON estimates that the Bio2G would have an external demand for its low grade heat (10–50 MW_{th}) during 3000-5000 h/year, thus up to around 250 GWh/yr. The corresponding total heat revenue depends on the recipient's opportunity cost, but assuming 250 SEK/MWh, this would be an income of around 60 MSEK/yr. In addition, their internal electricity production (16–24 MW_e, i.e. 128–192 GWh/yr) would be able to benefit income through green electrical certificates (150–160 SEK/MWh (42)).

If instead the bio-SNG plant is located next to one of the investigated forest industries, how is then the market for these two by-products changing? First, as regards the revenue from the electricity, the situation would most probably be unchanged since all the electricity produced by the internal bio-boiler is also used internally and is thus, independent of where the plant is being established. In contrast, as is also clear from the site descriptions given in ch. 5, the market for waste heat does not remain the same. A summary of heat excess and heat demands for the different forestry sites and its surroundings as of today is given in table 12. To also be able to speculate about the future possibilities, a column giving examples of larger potential thermal deposition sources for each site is also included. It can be concluded that the majority of these sites foresee difficulties to benefit additional surplus heat from a future biomass gasification plant as the majority of these already today have problems to exploit their heat excess, and no obvious benefit, with respect to the heat economy, in a co-existence is therefore expected. As can be seen in table 12, it is only Vaggeryd that claims that they do not have any heat excess, simultaneously as they and so also a nearby pellet factory express interest to utilize waste heat from future adjacent industrial activities.

Furthermore, even though that the majority of the studied forest industrial sites foresee difficulties to benefit additional heat excess based on current circumstances, it should be noted that this overall picture may change in the future. One could for example speculate that an increased capacity of waste heat that comes with an adjacent bio-SNG plant could make an investment in connecting sites today lacking connection to any (e.g. Fors–Avesta) or to a larger district heating network (e.g. Hyltebruk–Halmstad) beneficial. The same argument holds of course also for Värö, which should according to e.g. reference (43) have good opportunities to also provide Kungsbacka with district heating in the future. For this to be realized, it is required, however, that the waste heat from the forestry sites/bio-SNG plant is in competition with the heat produced in the larger waste incineration plants.

When it comes to Norrsundet and its future potentials for heat utilisation it is even more difficult to make any predictions. As described in ch. 5, it is unlikely that a district heating network is built in the immediate area, but there is a great potential for the development of new industries in place that might need to take advantage of waste heat; i.e. a possibility not to be neglected. Besides conventional industrial space heating and/or different drying processes, one such example is greenhouse cultivation. If watercourses are available, another alternative could be industrial fish-farming. An example of the latter is Carelian Caviar´s sturgeon breeding in Varkaus, Finland, which fish farming is supplied with waste heat from Stora Enso´s paper mill at the same site (45). In a Swedish context, and with respect to the studied sites, fish farming could be of special interest for Hyltebruk. Tiraholms Fisk is today running so called conventional bag fish cultivation in the lake of Bolmen around 25 km from Hyltebruk. They currently considering the possibility to expand their business also to include land-based fish farming (46). One possibility could be to run this activity adjacent to Hyltebruk paper mill, taking advantage of the waste heat produced at the site, the water of the river Nissan (to be recirculated) and the building that was left over at the site after that two of the paper machines were shut down (see ch. 5.1).

Table 12. Summary of amount of heat excess and heat demand, respectively, for the different industrial forestry locations, as of today and potentials. The number given for TODAY refers to the current amount of heat supplied by the industrial forestry site, whereas the number given for FUTURE POTENTIALS refers to the predicted future demand. To be noted that up to 400 GWh/yr of additional heat excess would approximately be available at each location if a bio-SNG (200 $MW_{BIO-SNG}$, up to 50 MW_{th} 8000 h/yr) also be erected next to existing forestry industry. [1]The given heat demand incl. both high- and low grade heat.

Location	Heat excess today (GWh/yr)	TODAY: Heat supply to the vicinity (GWh/yr)	FUTURE POTENTIALS: Potential heat demands in the vicinity (GWh/yr)
Hyltebruk	200–300	19 (District heating of Hylte)	19 - District heating of Hylte (44) 555 - District heating network of Halmstad (44) 50 - Derome´s pellet factory (47)
Värö	Ca 240	120 (District heating network of Varberg)	180-200 - District heating network of Varberg (44) 155 - District heating network of Kungsbacka (44)
Vaggeryd	0	0	105 - For biomass drying instead of currently applied LPG-drying (16) 40-170 - Neova pellet factory (17)
Braviken	Total unknown	Ca 80 (Sawmill)	Ca 80 – Sawmill (18) 1100 - District heating network of Norrköping (44)

Location	Heat excess today (GWh/yr)	TODAY: Heat supply to the vicinity (GWh/yr)	FUTURE POTENTIALS: Potential heat demands in the vicinity (GWh/yr)
Fors	≤400	0	220 - District heating network of Avesta (45)
Norrsundet	-	-	-

Another by-product that may bring an income for a gasification plant is carbon dioxide as this is removed from the product gas in one of the fuel processing steps (see figure 2). In this case, a close connection to a larger greenhouse cultivation such as a vegetable grower is advantageous which besides demanding waste heat is a carbon dioxide demanding industry (48, 49). According to the reference (50), a larger Swedish vegetable grower consumes in average 20–60 kg/m^2 CO_2 per year and starting from current price for liquid-based carbon dioxide (1–3 SEK/kg CO_2 (50)), this corresponds, for the greenhouse grower, to a cost of 20–90 SEK/yr m^2. The cultivation area of one such cultivator typically ranges from 1 000–10 000 m^2 (51), even though vegetable greenhouses as large as 80 000 m^2 also do exist (Sydgrönt, Trelleborg). E.ON estimates that the annual production of CO_2 at Bio2G will be in the order of 570 000 ton (see table 1); thus, an amount that could fully cover the demand of carbon dioxide for a typical greenhouse cultivation, and in turn also contribute with a revenue for the bio-SNG plant. Currently, greenhouse cultivators either buy liquid-based carbon dioxide or produce their own through combustion of natural gas or LPG. Today, no vegetable greenhouse cultivations or other carbon dioxide demanding industries are situated nearby any of the studied sites.

6.8. Adjacent bio-SNG production – a marketing opportunity lowing the CO_2 print

Another possible commercial gain by integrating a bio-SNG plant as a part of an already existing forest industry, except from the economic aspects, is that it would make it possible for the company owning the industry to lower their CO_2-emissions. For example, a forest industry like Södra could make their transports “green” in the sense that no fossil fuels would be needed for transportation, with trucks running on self-produced bio-SNG. In reference (28) a value of 0.5% of the energy content in the material (here branches and tops) is needed for transportation of the biofuel from the forest (based on an average transportation distance of 50–60 km). Another, more up-to-date, study gives an average value of the energy consumption needed for collecting and transporting branches and tops of 46 kWh/m^3fub (51). This corresponds to ~2% of the energy content in the material itself (assuming an energy content of 2.3 MWh/m^3fub (52).

6.9. 100 or 200 MW Bio-SNG plant – pros and cons

As E.ONs Bio2G plant has been used as reference for a stand-alone plant in this project, the value analysis has mainly been based on the establishment of a 200 MW bio-SNG large plant. However, this does not mean that 200 MW is necessarily the only and the most ultimate design capacity to aim for at an existing forestry site. Even though scale advantageous are to be expected and thus, a general lower specific investment cost for a 200 MW cf. a 100 MW plant, a design capacity of 100 MW bio-SNG or even smaller could be more advantageous with respect to the profitability (7). One such critical perspective is the biomass availability and the biomass cost. For smaller plants, it is more likely that the supply of biomass feed-stock can be met by the resources nearby, which in turn generally results in a cheaper fuel cost. Another perspective is the possibility for utilisation of the waste heat. The larger the plant, the larger amount of waste heat produced. Since the market for heat utilisation generally becomes smaller in the vicinity to an existing forestry site compared to when it is built up in an urban area, the amount of waste heat from a 50–100 MW plant compared to a 200 MW could be easier to match.

7. Summarizing discussion

This work points out that benefits could be gained by co-locating a larger bio-SNG plant at an existing industrial forestry site compared to building it as a stand-alone plant, potentially lowering both the investment and the operation costs. From a general view-point, identified values are:

- The vicinity to the forest – cutting the transportation costs of raw material into the site and hence, reducing the biomass cost for the bio-SNG production. The transportation cost can be in the range of 30% or more of the total biomass cost, depending on the biomass capture radius, the type(s) of transportation means applied and the necessary number of reloading, etcetera.

- By-products such as saw dust and bark available for bio-SNG production lowering the total raw biomass material cost.

- More secure biomass supply, since the forest industries are either owned or working in close collaboration with forest owners, reducing the need for larger storage capacities and most probably also lowering the biomass cost for the bio-SNG production.

- Available prepared land for wood yard capacity or other activity needed for the bio-SNG plant reducing the investment cost of the bio-SNG plant.

- Logistics for large scale biomass transportation into the site (road, rail and sea) already in place, cutting the investment cost of the bio-SNG plant, so also most probably the total biomass cost.

- Free capacity in already existing machinery park (chippers, crushers, dryers, etc.) to which the new installations can be adapted, further cutting the investment cost of the bio-SNG plant.

- Free staff available, with valuable know-how in large scale fuel handling of solid biomass material, control and maintenance of larger industry, reducing the number of shift workers and hence, cutting the operation costs of the bio-SNG plant.

- Possibility to make the forest industry´s transportations “green”.

Furthermore, the results also clearly illustrate the value of being connected or located close-by a gas grid. Thus, enabling the same advantageous as for Bio2G, i.e. safe and economic green gas transport directly from the production site to the market, so also a back-up solution at operation interruptions and at start-ups. To exemplify the economic value in figures, Hyltebruk has the possibility to transport gas for a total cost of 50 SEK/MWh to a typical vehicle gas station (10 GWh/yr), which is significantly less compared to a bio-SNG plant that needs to rely on solely flatbed transportation (120-180 SEK/MWh incl. cost for gas storage). Furthermore, the results also indicate that it could be more economical to connect sites such as Vaggeryd (40 km from the gas grid), to the national gas grid, than relying on solely flatbed gas transport. Such an investment would roughly cost 300 MSEK; an investment that on an annual basis would add around 20 % to the total gas transport cost, i.e. ending up at 70 SEK/MWh (10 GWh/yr).

One common clear challenge for the majority of the studied forestry sites as of today´s situation is the difficulty of finding outlets for the surplus heat. This loss of heat revenue would however be offset by the cheaper cost of biomass. For example, assuming an average biomass cost of 190 SEK/MWh for a stand-alone plant as planned for Bio2G, this would correspond to a total annual biomass cost of 530 MSEK. If this amount of biomass instead could be purchased for around 160 SEK/MWh, an annual gain of around 80 MSEK could be achieved, thus in the same order as the estimated heat revenue for Bio2G. This balance is therefore of vital importance for the decision on which design capacity is most appropriate for a certain location.

Looking more into the details, the results show that the values that could be obtained when co-locating a larger bio-SNG plant varies from one forestry site to another dependent on the site´s nature and location. The major pros and cons of the selected forestry sites are listed in table 13a-f. As the biomass cost (including transport into the site) is one of the most critical parameters determining the production cost of the bio-SNG, forestry sites having high availability to low cost biomass are evidently the very advantageous. In this respect, a forestry site situated in-land in a region with a high forestry growth such as Vaggeryd and Hyltebruk in Götaland are frontrunners. But also a site such as Värö is in this regard of special interest, having a significant excess of low-cost bark available. Closeness to the gas grid is seemingly another critical issue. In this connection, locations such as Hyltebruk and Värö have a big lead. Besides these two critical aspects, also other parameters may in the end play an important role. One such example is the heat demand in the vicinity. Another is the regional need for new job creation. Regarding the heat demand, Vaggeryd is the location that today stands out, whereas Norrsundet and Hyltebruk are those locations that seem to have the greatest need for new job creation. Finally, this report also indicates that the conditions that apply today for several of the investigated industrial forestry sites may well have completely changed within a decade of perspective. Norrsundet, for example, may not be the obvious choice of today as site for a new bio-SNG plant. But if the plans for a new gas grid (Norrsundet-Sandviken-Hofors) with a LNG terminal on this site becomes a reality, the conditions for bio-SNG production would instead turn out to become very good.

Table 13a–f. Summary of the major pros and cons for establishing a larger bio-SNG plant at the different forestry sites.

13a. Hyltebruk

Pros	Cons
• High and secure biomass availability • Staff with good knowledge in biomass handling and large scale industrial production → synergies • ≤ 1 km to the transmission gas grid • Free zoned land available (≈ 70 000 m^2) • Industrial site with a declining production → strong driving force for establishing new industrial activities/expanding the product portofolio at the site	• No direct access to boat nor train transport. Reloading of biomass today necessary at the site when railway transport is applied. • No additional demand for residual heat.

13b. Värö

Pros	Cons
• High and secure biomass availability • Staff with good knowledge in biomass handling and large scale industrial production → synergies • Excellent logistics for biomass transport into the site (road, train, boat). • ≤ 10 km to the transmission gas grid • Excess of bark (150 000 ton) and black liquor available. Looking for new uses for the bark. Soon 260 000 ton bark available; enough to produce ca 0,4 TWh bio-SNG. • Industrial site under expansion → low risk for close down and more safe co-integration	• No additional demand for residual heat • No free available zoned land • Industrial site under expansion → weak driving force for establishing new industrial activities at the site

13c. Vaggeryd

Pros	Cons
• High and secure biomass availability. • Located in-land forest → biomass can be transported into the site from all directions. • Located solely ≈ 40 km from Stockaryd railway terminal (Småland) • Staff with good knowledge in biomass handling and large scale industrial production → synergies • Very large free zoned land available (≈ 1 000 000 m^2) • Demand for residual heat (up to 32 MW_{th}) • "Only" 40 km from the gas grid	• 40 km to gas grid • No direct access to train nor boat transport, reloading thus necessary for all biomass transport except for road

13d. Braviken

Pros	Cons
• High and secure biomass availability • Staff with good knowledge in biomass handling and large scale industrial production → synergies • Good logistics for biomass transport into the site (road, train and boat) • Free zoned land available (100 000 m^2) • Declining production capacity → Fairly strong driving force to establish new industrial activities	• Very far from gas grid as of today, ≈ 170 km from potential future gas grid in Mälardalen • No additional demand for residual heat

13e. Fors

Pros	Cons
• High and secure biomass availability • Located in-land forest → biomass can be transported into the site from all directions. • Staff with good knowledge in biomass handling and large scale industrial production → synergies • Good logistics for biomass transport into the site (road, soon also train). Spur-line into the site under planning. • Free zoned land available (30 000 m^2) • 40–50 km to potential future gas grid between Norrsundet-Sandviken-Hofors	• No direct access to boat transport • Very far from gas grid as of today, • No additional demand for residual heat

13f. Norrsundet

Pros	Cons
• Excellent logistics for biomass transport into the site available (road, train and boat) • Large zoned land available (660 000 m^2) • Industrial building and belt dryer available (26 MW_{th}, dated 2009) • A couple of tenths of people available with good expertise in fuel handling and large-scale production • Looking for new large scale industrial activities → opportunity • Future LNG-terminal in Norrsundet under discussion, to be connected to a potential future regional gas grid between Norrsundet-Sandviken-Hofors	• Very far from gas grid as of today • No additional demand for residual heat

8. Conclusions

This study has investigated and analyzed added values of co-locating a new large bio-SNG plant with an existing industrial forestry site compared to building it as a stand-alone plant. The focus has been on biomass availability, logistics, handling and the available market for the products. A closer study and comparison of six different potential locations have been performed, i.e. Hyltebruk, Värö, Vaggeryd, Braviken, Fors and Norrsundet. The analysis has been carried out with respect to the current situation and what could be expected at the sites in a 10-year perspective.

The results show that several benefits could be gained by co-locating a larger bio-SNG plant at an existing forest industrial site compared to building it as a stand-alone plant, potentially lowering both the investment and the operation costs. The most decisive parameter is the availability of low cost biomass in combination with the closeness to a gas grid. Other examples are valuable know-how in large-scale biomass handling, personnel synergy effects in the operation and maintenance and regional needs for new job creations. Based on today´s conditions, Hyltebruk and Värö stand out as frontrunning locations. However, in a 10-year perspective, some of the other sites could also be suitable locations for the current proposal. One such site is Vaggeryd, surrounded by forest with excellent growth in combination with the fact that it is situated only 40 km from the national gas grid. Another is Norrsundet, provided that the discussed regional gas grid Hofors-Sandviken with a connecting LNG terminal in Norrsundet is in place.

Furthermore, one common clear challenge for the majority of the studied industrial forestry sites as of today´s situation is the difficulty of finding outlets for the surplus heat. This loss of heat revenue would however be offset by the cheaper cost of biomass.

Finally, a summary of the different influencing perspectives and which of the locations that, on the basis of these indicators, could benefit most from a new bio-SNG establishment is given in table 14. The results are referring to today´s conditions and so also to on-going discussions and plans for the future.

Table 14. Location(s) that could most benefit from a new establishment of a large bio-SNG plant based from different critical perspectives.

Decisive perspective	Suitable location(s)
Vicinity to forest, high biomass availability	Vaggeryd, Hyltebruk
Low cost by-products available	Värö
Biomass logistics (road, rail, boat)	Värö, Braviken, Norrsundet
Gas storage, gas transport and gas back-up (gas grid and/or LNG-harbour)	Hyltebruk, Värö (TODAY) Vaggeryd and Norrsundet (POTENTIAL)
Heat demand	Vaggeryd (TODAY) Värö and Braviken (POTENTIAL)
Regional job needs	Hyltebruk, Norrsundet

9. Further work

The next step of this work is to further, in more detail, investigate the industrial forestry sites that in this study stand out as the most beneficial for the co-location of a bio-SNG plant, i.e. Hyltebruk and Värö. This future work needs then to also include the different processes of the bio-SNG production line answering questions such as which technologies and production capacities, etc., would be the most beneficial to aim for. Existing auxiliary systems at the industrial forestry sites are of importance to investigate as well, such as bio-boilers and water cooling systems, and how these could possibly be used jointly at a co-location with a new bio-SNG plant.

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Gasification for bio-SNG production adjacent to a forest industry

För att Sveriges vision om en fossil-oberoende fordonsflotta 2030 skall bli till verklighet krävs att produktion av biobränsle, t.ex. biogas, intensifieras och storskaliga förgasningsanläggningar etableras. För att de skall fungera måste också logistiken kring fabriken fungera. Genom att förlägga förgasningsanläggningen intill en befintlig skogsindustri kan kostnaderna minska. Men möjligheten till att uppnå synergieffekter mellan industrierna skiljer sig markant från en lokalisering till en annan. I denna studie har man närmare undersökt förutsättningarna för en samlokalisering av en ny förgasningsanläggning för produktion av biometan vid 6 svenska skogsindustrier (Hyltebruk, Värö, Vaggeryd, Braviken, Fors, Norrsundet). Värö och Hyltebruk lyfts upp som de mest intressanta lokaliseringarna att titta närmast vidare på, medan Vaggeryd och Norrsundet spås kunna bli högst intressanta längre fram i tiden.

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