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A Techno-Economic Study of a Biomass Gasification Plant for the Production of Transport Biofuel for Small Communities

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Abstract

A techno-economic feasibility study of liquid bio-fuel production from biomass to meet the demand for public transport in small communities is presented. The methodology adopted in this work is based on calculating the demand of fuels required by transport sector and then estimating the amount of available biomass from various sources which can be treated to produce bio-fuels to meet the demand within the region. Depending on demand and available biomass feedstock, size and type of the gasification plant are specified. Narvik, a town in the northern part of Norway, is considered as a case study. The current demand of diesel for public transport in Narvik was calculated. The main sources of biomass in the region under consideration come basically from forests and municipal solid waste. It was found out that the potential of producing biofuel is more than three times the fuel demand for public transport, which means that excess biofuel produced can be used in other sectors such as heating. A downdraft gasifier of 6.0 MW was considered adequate to produce the required amount of biofuel. Cost analysis was performed where capital cost, operational and maintenance (O&M) costs for the biomass pre-treatment processes, the gasification plant and the gas to liquid (GTL) plant were considered in the assessment. It was concluded that the payback period of the project could be achieved within four years. The study demonstrated that biomass gasification offers small communities a means to cover their energy demand for public transport using local biomass feedstock and fulfils environmental targets of the community.

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Keywords: Biomass Gasification, biofuel, gas to liquid (GTL), waste treatment, Municipal Solid Waste (MSW), carbon-neutral, Syngas

1. Introduction

The energy sector in Norway is characterized by massive contribution from hydropower resources. Almost 99% of electricity in Norway is generated through hydropower, which has lowered the prices of electricity in the country.

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Nomenclature

GTL	gas to liquid
MSW	Municipal Solid Waste
FT	Fischer-Tropsch
CBA	Cost Benefit Analysis
PBP	Payback Period

Furthermore, it is estimated that the renewable energy sector in Norway has a share of 58% of gross energy consumed in the country, so Norway is a pioneer in utilizing renewable energy resources. Of that share, hydropower contributes with 50%, while bioenergy contributes with only 6% [1]. On the other hand, the market in Norway is known for high fuel prices, despite the fact that the country owns large oil and gas reserves. Prices of oil and gas are among the highest in the world, and this reflects on the prices of transportation, which is a major consumer of liquid fuel.

Norway has witnessed an increase in CO_2 emissions from energy use by 10% since 2000. The main contributor to this increase is transportation (36%), oil and gas extraction (26%), and industry (18%) [2]. Multiple solutions can be proposed to reduce CO_2 emissions from transportation sector, for example, increasing the dependence on electric vehicles (EVs) or utilizing biomass resources to produce carbon-neutral liquid fuel such as biodiesel derived from biomass, which is plagiarised from biological organisms such as plants and animal matter. Many conversion processes are available to convert biomass into biofuel such as chemical, biological and thermochemical conversion. The resulting biofuel can be either in solid, liquid or gas form. Examples of biofuel can be bio-ethanol, bio-diesel and bio-hydrogen. Almost 2.7% of world's consumption of fuel for road transport is made up of biofuels, where bio-ethanol and bio-diesel make the largest contribution [3].

Due to the fact that the major contributor of biomass is plant matter, there have been many debates over the utilization of biomass to produce energy. This issue can create a conflict over the priorities when it comes to the fact that there are poverty and hunger in the world. It is argued that it would be more reasonable to cultivate land and plant crops to feed people rather than produce energy, such conflict is indicated in the old and continuing "Food vs. Fuel" debate. Furthermore, the excessive use of wood from forests for fuel production can lead to deforestation and soil erosion, loss of biodiversity and a negative impact on water resources. In the light of such economic, social and environmental issues related to using agricultural resources and energy crops for the production of biofuel, a statistical study of biomass resources in Norway is presented in this paper, where the potentially available amount of forest resources for biomass purposes and the organic content in Municipal Solid Waste (MSW) are considered for the production of biofuel for public transport in small communities.

2. Major biomass resources in Norway

The major source of biomass in Norway is forests which cover 120,000 Km^2, which is about 37% of the land area of Norway. The potential of biomass from forests for energy production in Norway as a total is estimated between 86 and 108 peta-Joule (PJ= 10^{15} joule) [4]. The total growing stock is about 910 million m^3. The annual growth of the stock in forests is 25 million m^3, where less than half of the forest stock (44%) is being harvested annually [5]. This means that almost 11 million m^3 of wood is harvested annually, which can be used as biomass.

The common tree species in Norway used as biomass is Norway-spruce. The basic wood density for this type of trees is 373 kg/m^3 [4], which indicates that nearly 4 million tons of Norway-spruce wood is available annually. This calculation is simplified in figure 1.

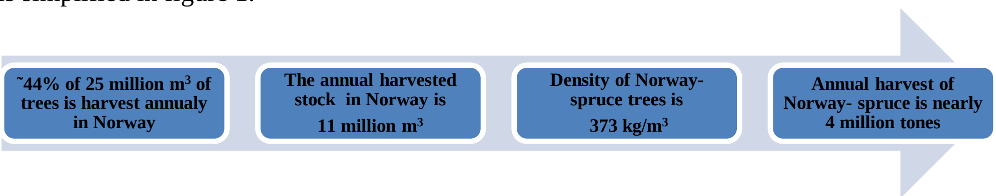


Figure 1: Annually available biomass from forests

Municipal Solid Waste (MSW) is the second major contributor to biomass in Norway. According to statistics from Statistics Norway (Statistisk sentralbyrå), each inhabitant in Norway discards nearly 470 kg of waste each year [6]. The organic content in the MSW includes food waste, paper, wool, leather, cotton, wood waste, etc. The fraction of bio/waste in this output can be assumed as 70 % of the total MSW [7], which gives 330 kg per capita per year, of which, 60% is dry content, so the amount of biomass generated from MSW is 198 kg per capita per year. From those two major sources of biomass, a significant amount of bio-fuel can be produced, and used to subsidize the need for fossil fuels, which leads to reducing CO_2 emissions from the transport sector.

3. Gasification technology for waste treatment

Gasification is a thermo-chemical process, where incomplete or partial combustion of biomass converts it into flammable gases. While complete combustion oxidizes the hydrogen and carbon contents in the feedstock or biomass and forms water and carbon dioxide, gasification results in the production of hydrogen and carbon resulting in gases with higher (H:C) ratio. A gasification process needs either oxygen, steam or air, known as gasifying agents, in order to convert the solid feedstock or biomass into gas or liquid fuel. Oxygen is known to be the best gasifying agent; however, using oxygen is more costly. Moreover, having high amount of oxygen, the gasification process shifts to combustion and the resulting product instead of being "fuel gas" becomes "flue gas".

The resulting gas from gasification is *Syngas*, which is also known as synthesis gas, producer gas, or reformer gas, depending on the production technique used, is a mixture of hydrogen (H_2), carbon monoxide (CO), small amounts of carbon dioxide (CO_2) and methane (CH_4). It may also contain nitrogen in case air was used as a gasification agent [8]. Syngas may also contain some impurities like tar and ash, which can be removed via further processing or can be either recovered or redirected to the gasifier. The composition of the syngas is very dependent on the source fuel (i.e. biomass) fed into the gasifier, it is also dependent on the type and technology of the gasifier and its design and thus, the same type of waste may give different calorific values when using it in different types of gasifiers. The amount of produced syngas depends significantly on the total amount of carbon in the waste material fed into the gasifier. On average, one kilogram of wood biomass produces 2.5 m^3 of syngas [9]. The density of syngas is 0.95 kg/m^3 [10], which gives almost 2.4 kg of syngas from each kg of wood biomass. The most important characteristic about syngas is the amount of hydrogen and carbon monoxide it contains, the higher it contains of these two gases, the higher quality the syngas is. Nitrogen presence in the syngas dilutes the gas, this can occur due to the application of ambient air as the gasification agent, in which case the resulting syngas contains about 50-60% of its composition as non-combustible nitrogen [9], which is why it is more beneficial to use oxygen as a gasification agent instead of air. However the cost of using oxygen in gasification increases the cost of production.

4. Syngas conversion to Bio-diesel

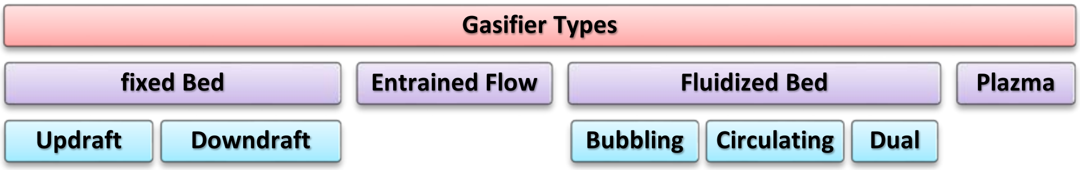
Syngas can be subjected to specific chemical processes in order to produce other liquid fuels like diesel, methanol, ethanol and hydrogen. In this study, we are mainly concerned with bio-diesel production via Fischer-Tropsch synthesis in order to use the produced fuel for transportation purposes, and to determine how much the product can contribute to the public transportation sector in a small community such as Narvik.

Fischer-Tropsch synthesis is a series of chemical reactions that convert the hydrogen (H_2) and carbon monoxide (CO) found in the syngas into liquid hydrocarbons. The reactions take place over a catalyst most commonly based on iron or cobalt [11]. The Fischer-Tropsch process takes place at temperatures between 150 ^oC and 300^oC, with pressure typically between 20 and 40 bar. In average, about 60% to 75% of purified syngas can be converted to FT-fuels [12]. One of the main requirements for FT-reaction is that the syngas produced from gasification process is highly pure. In case the syngas contains high amounts of Sulphur, it will inhibit the catalyst activity and reduce its lifetime. Tar would also reduce the catalyst surface area and its lifetime. The second most important factor is the H_2/CO ratio in the syngas, optimally; it has to be between 1.7 and 2.15 for maximised FT-production [13]. In case the ratio was lower, hydrogen amount in the syngas can be increased with the aid of water-gas shift reaction, where part of CO reacts with steam to generate increased amounts of H_2 and CO_2. Although the amount of CO_2 would increase in this case, but it is more tolerable than the poisonous CO.

5. Gasifier selection

There are various types of gasification technologies that have been developed for converting biomass into fuel. Many types were developed for heat and power generation, other types were developed to produce liquid fuel. Classification of gasifiers depends on certain characteristics like: the way the biomass is fed into the gasifier, either from the top or the side of the gasifier, the gasification agent or oxidant used for the gasification process (air, oxygen or steam), the range of temperatures and pressures the gasifier operates at, the source of heat provided for the gasifier and whether it was by partially combusting some of the biomass in the gasifier (this is called directly heated), or by using an external source (Indirectly heated), such as circulating steam or an inert material. The types of gasifiers can be divided into the following categories shown in Table 1 [11].

Table 1 Gasifier types



In this study, the downdraft gasifier has been assessed as the best gasifier for our application for the following reasons:

1. It has a simple design, which reduces material and running costs.
2. Construction and manufacturing of the gasifier is not complicated.
3. It is the most commonly used gasifier, especially when dealing with limited amounts of biomass and MSW.
4. Its widespread implementation means that more data on operation and maintenance of the system is readily available.
5. It is not sensitive to tar and moisture content of the biomass, which means that the produced syngas contains low tar, which is a very important point when dealing with engine applications. The case is different for the updraft gasifier, which falls in the same category as a fixed bed gasifier, which is more sensitive to tar and hence, it is not suitable for engine applications.

6. The Downdraft Gasifier

Downdraft Gasification consists of four consecutive processes: Drying, Pyrolysis, Combustion and Reduction. Each process is performed in a separate zone in the gasifier, however there is an overlap between these zones. The reactor is usually the largest part in a gasification system, and it is the place where biomass is fed, reacted and where syngas leaves for further cleaning and cooling. The design of the reactor is vertical, which means that these zones are arranged vertically above each other, as shown in figure 2. What is special about this type of downdraft gasifiers is that the combustion zone is throated in order to makes it easier to keep a constant temperature in the combustion zone, while the gases are forced into it. It is very important to dry the biomass and make it ready for the gasification processes. Drying can be done inside or outside the gasifier. In the drying zone, biomass is heated up to 100^{o}C, the needed heat for drying can be from the gasifier itself, by burning some of the biomass in the combustion zone. Pyrolysis is the next process, where biomass structure breaks down, char is formed and volatiles, also called tar gases, like methane and hydrogen are released, this process is also called a (De-volatilization) process [14]. Gas generated in the pyrolysis zone mixes with the moisture coming from the drying zone and flows downward to the combustion zone. Heat needed for drying and pyrolysis, which takes place at nearly 270^{o}C, can be obtained by burning some of the biomass inside the gasifier in the combustion zone.

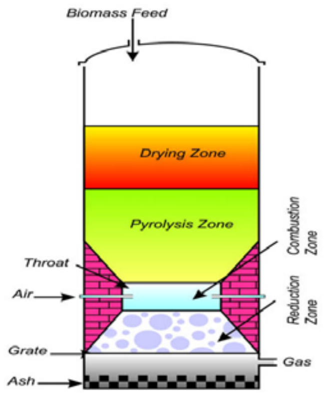


Figure 2: Imbert-Type Downdraft Gasifier**.**

A limited and controlled amount of air is supplied to the combustion zone through nozzles, however, oxygen or steam can also be used. Part of the carbon in the form of char is burnt to form carbon dioxide according to formula (1):

$$C + O_2 \xrightarrow{yields} CO_2 \quad (+\,393\ MJ/kg\ mole) \tag{1}$$

Furthermore, through oxidation of hydrogen, water is formed according to formula (2):

$$2H_2 + O_2 \xrightarrow{yields} 2H_2O \quad (+\,242\ MJ/kg\ mole) \tag{2}$$

In addition, a lot of heat is released during the combustion process; the temperature can reach up to 1400ºC. This heat is important for the final reduction process. The main gasification reactions take place in the reduction zone, the first main reaction is when carbon in the form of char reacts with carbon dioxide to form carbon monoxide according to formula (3), [15]:

$$C + CO_2 \xrightarrow{yields} 2CO \quad (-\,164.9\ MJ/kg\ mole) \tag{3}$$

The second main reaction is when carbon also reacts with steam forming carbon monoxide and hydrogen as shown in formula (4):

$$C + H_2O \xrightarrow{yields} H_2 + CO \quad (-\,122.6\ MJ/kg\ mole) \tag{4}$$

Moreover, some of the char (C) reacts with hydrogen (H) to create methane (CH_4). The water gas shift reaction reaches equilibrium quickly at the temperature of the gasifier in this process, which increases the amount of hydrogen by reacting carbon monoxide with water and forming carbon dioxide and hydrogen according to formula (5), [15]:

$$CO + H_2O \xrightarrow{yields} CO_2 + H_2 \quad (+\,42.3\ MJ/kg\ mole) \tag{5}$$

Following to this step, syngas is formed and leaves the downdraft gasifier from its bottom for further treatment in order to be converted into bio-fuel.

7. Syngas composition from a downdraft gasifier

The composition of produced syngas depends very much on the type of biomass and the type of gasifier. However, the calorific value of the syngas produced in a downdraft gasifier using air as oxidant is between 4 and 5.6 MJ/Nm^3. The typical composition of syngas produced by a downdraft gasifier contains the following ratios of gases by their volume as shown in figure 3, [16]:

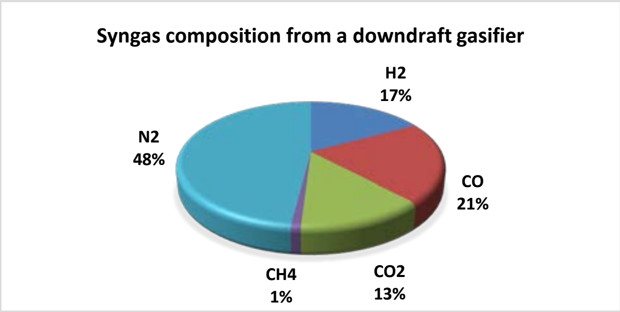


Figure 3 Typical composition of syngas produced by downdraft gasifier (% by volume)

8. Estimated potential amount of biofuels in Narvik

Narvik is the third-largest municipality in terms of population in Nordland County in Norway, with about 60,000 inhabitants and an area of ca. 2000 Km^2. The existing waste management companies that handle such waste have to be major stakeholders in the project. On the basis of the previous information and estimates of domestic biological waste in Narvik municipality, it was concluded that the total amount of biomass gathered from forests and municipal solid waste is about 27,000 tons annually distributed as shown in figure 4:

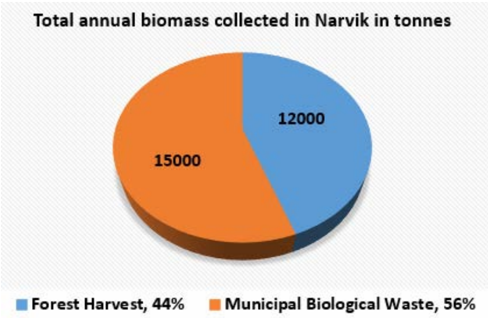


Figure 4 Total annual biomass collected in Narvik in tonnes

At present, three waste companies in the northern part of Nordland County, are responsible for the collection and management of organic waste. A lot of waste from Narvik, and neighbouring municipalities is transported to Sweden, where it is incinerated [17]. The costs for transportation and gate fee for incineration and secondary landfill are considerable. Norwegian Environmental Agency and many environmental groups have conflicting views regarding the environmental benefits of transporting waste to over 1000km. In this regard, the possibility of treating biomass locally to produce useful energy should be attractive if the option offers economic benefits to the investors.
Research shows that it is possible to produce 0.122 kg of bio-diesel from one kg of dry biomass using Choren and Scanarc processes [18]. Therefore, just taking the amount of biomass in Narvik region, approximately 3,294 tons of bio-diesel can be produced annually. The calculation is shown in figure 5.

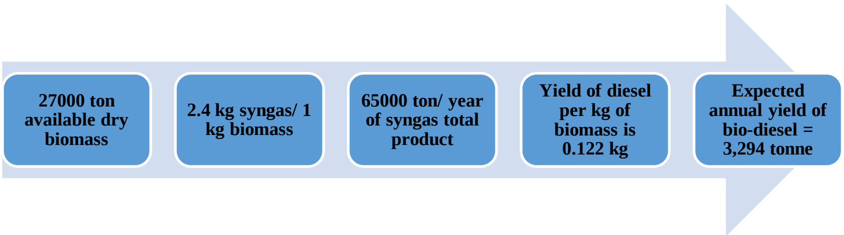


Figure 5 Expected annual yield of bio-diesel

Table 2 summarizes the expected annual quantities of syngas, bio-diesel and bio-hydrogen producible from 27,000 tons of biomass collected in Narvik.

Table 2 Approximate amount of liquid fuel producible from 27,000 tons of biomass

Product	Amount produced in (tons*)	Amount produced in (1000 litres*)
Syngas	65,000	67,500
Bio-diesel	3,294	3,875
Bio-hydrogen	814.7	11,475

**Conversion is performed depending on the following densities: syngas: 0.95 kg/l, diesel: 0.85kg/l and liquid hydrogen: 0.071kg/l.*

9. Estimating the demand

The average fuel consumption of a 60 passenger city bus is 6.1 miles per gallon (mpg) of diesel*i.e.* 46.3 litres for each 100 kilometres [19]. The number of public bus routes run by Narvik commune to connect Narvik town and with other villages and cities within the commune is 15 routes. The average annual distance travelled by all buses was found to be 2,340,000 km. The total annual diesel consumption of all buses is equal to;

$$Annual\ \ diesel\ consumption\ = 2{,}340{,}000 \times 46/100 = 1{,}076{,}400\ liters \quad (6)$$

This shows that the annual consumption of diesel in the public transport sector is only 28% of the biofuel potential from the biomass locally available. Next step is to calculate the capacity of the gasifier that can produce the required amount of energy (biofuel) every day. Figure 7 shows the estimation of the capacity of the plant:

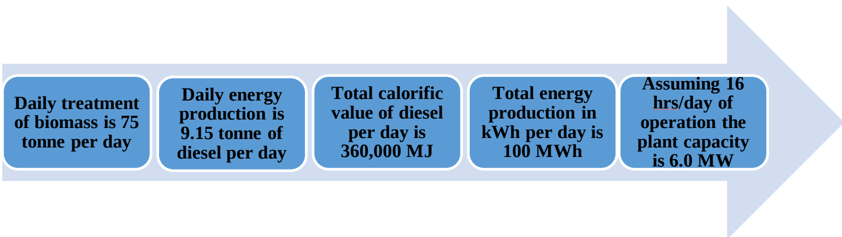


Figure 6: Calculation of gasification plant capacity

It is assumed that the gasification plant will operate for 16 hours per day, hence, the power capacity of the gasification plant would be 6.0 MW.

10. Cost analysis

The total capital cost for the whole installation and the total annual O&M cost in million NOK are presented in table (3) below:

Table 3: Total capital cost for the whole system and total annual O&M cost in million NOK

Cost category	Capital Cost (million NOK)	O&M Annual Cost (million NOK)
Biomass pre-treatment	9.50	8.57
Gasification plant	71.50	9.64
GTL plant	35.00	5.02
Total Cost (million NOK)	116.00	23.23

11. Payback period of the plant

The lifetime of the plant was modestly assumed to be 10 years in this study, based on daily operation of 16 hours/day. It is well understood that, if the plant was well maintained, the lifetime could be longer than 10 years. Table 4 presents that the cumulative benefits exceed the cumulative costs after four years of operation, which indicates that the payback period of the proposed plant is four years.

Table 4: cumulative costs and benefits

Year	Cumulative cost (million NOK)	Cumulative benefit (million NOK)
1	139.23	054.25
2	162.46	108.50
3	185.69	162.75
4	**208.92**	**217.00**
5	232.15	271.25
6	255.38	325.50
7	278.61	379.75
8	301.84	434.00
9	325.07	488.25
10	348.30	542.50

12. Conclusions

Through investigations of the various gasification technologies it was established that the downdraft gasification technology was best suited for meeting the demand for small communities, where the city of Narvik was considered as a study case. Due to the simplicity and flexibility of downdraft gasification plant, it is most suited for small-scale applications.

The availability of biomass resources in Narvik region suitable for producing useful bio energy was beyond expectations. It was found that the potential of the feedstock collected from waste and forest in Narvik municipality is about three times more than the demand for biodiesel for public transport requirements.

The treatment of waste is an imperative issue and considerably costs the municipality. However, treating the bio-waste using gasification methods can turn this waste into a source of revenue for the municipality, thereby, achieving two targets at one stroke where waste disposal can also lead to the production of energy. Any amount of petroleum based fuels replaced by biofuel derived from biomass will result into reducing CO_2 emissions as the CO2 produced from combustion of biofuel is neutral. A further advantage, the residual ash can be used as soil improver and fertiliser.

In terms of economic benefits, Cost Benefit Analysis (CBA) of gasification shows that the Payback Period (PBP) of the gasification plant in this context is very feasible with a payback period of 4 years. This shows that the gasification plant for treating bio-waste to produce bio fuels for transport offers environmental benefits and the proposal is also attractive to potential investors.

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