Chapter 11

A Value Chain Analysis for Bioenergy Production from Biomass and Biodegradable Waste: A Case Study in Northern Norway

Hao Yu, Elisabeth Román and Wei Deng Solvang

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.72346

Abstract

During the past decades, the concerns of the depletion of fossil fuels and global warming caused by excess GHG emissions have become the most important driving force for the development and utilization of renewable energy resources. The successful experiences from the EU-28 have proved that bioenergy production from biomass and biodegradable waste is the most reliable and promising solution in today's renewable energy market. This chapter presents a general model for value chain analysis of bioenergy production from biomass and biodegradable waste. In addition, a feasibility study for establishing a bioenergy plant in the northern part of Norway is given to discuss the opportunities and challenges of bioenergy production. The feedstock of the planned bioenergy plant is from local agriculture, waste management sector, fishery and livestock industry. Value chain analysis is used to balance the economic and environmental influences of the bioenergy production in the area. Furthermore, suggestions for resolving the challenges and minimizing the potential risks of bioenergy production are also discussed in this chapter.

Keywords: value chain analysis, biodegradable waste, biomass, bioenergy, energy production

1. Introduction

Bioenergy production from biomass and biodegradable waste has received increasing focus due to recent acceleration in depletion of fossil fuels. The portion of renewable energies counted only 11% of total energy consumption while 74% is fossil energy in EU-28 in 2012 (**Figure 1(a)**) [1]. The heavy dependency on fossil fuels has resulted in two critical issues. First, fossil fuel is non-renewable and cannot be replenished by nature within a reasonable

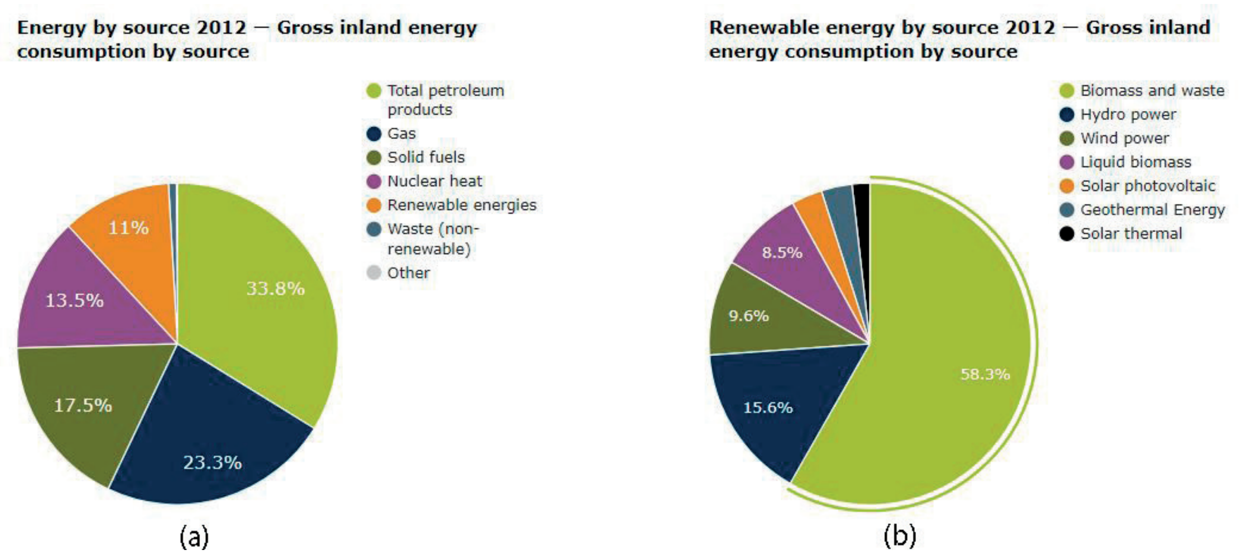


Figure 1. (a) Gross inland energy consumption by source of the EU-28 in 2012 and (b) renewable energy consumption by source of the EU-28 in 2012 [1].

timeframe. Moreover, the over-exploration and exponentially increasing consumption in recent years accelerate the depletion of fossil fuels. The estimated lifespan for the reserves of crude oil, natural gas and coal is approximately 35, 37 and 107 years, respectively [2]. The development of renewable energy resources becomes therefore of significant importance to meet energy demand in the near future. Second, the greenhouse gas (GHG) emission related to energy production and consumption from fossil fuels has played an important role to the global warming and climate change [3]. Both of them are believed to be the most significant challenges in the twenty-first century, which may lead to severe consequences for human's existence [4]. Due to these reasons, extensive efforts have been devoted in reducing GHG emissions in the past few decades. One of the most promising solutions to the abovementioned challenges is the explosion of renewable resources, i.e. wind, solar, tidal, biomass, etc., which not only provide an attractive alternative for energy production but also contribute to the mitigation of GHG emissions.

Bioenergy production from biomass and biodegradable waste is the most reliable renewable energy resource, which occupies predominant share of today's marketplace [5]. As shown in **Figure 1(b)**, the consumption of energy generated by biomass and biodegradable waste, liquid biomass, hydropower and wind power are 58.3, 8.5, 15.6 and 9.6%, respectively, and the other renewable resources including solar thermal, solar photovoltaic and geothermal constitute only 8% of the total consumption [1]. The reason for this high portion of bioenergy production in Europe is mainly due to the long-term efforts on developing legislative mechanism and technological means for recovering energy from biomass and biodegradable waste. For example, EU Landfill Directive (Council Directive 1999/31/EC [6]) implemented in 1999 sets the periodic target for the member states, and since then the amount of the biodegradable waste ended up in landfill has been dramatically reduced. EU Renewable Directive (Directive 2001/77/EC [7]) was implemented in 2001 and repealed in 2009 (Directive 2009/28/EC [8]) for promoting more applications of renewable energy resources. This has been followed up by Norwegian authority with a White Paper on Norwegian climate policies [9]. The White Paper documented particularly the large emissions of GHG from agriculture industry and waste management in Norway, and a specific goal is also stated to develop more bioenergy production plants in Norway. A joint treatment of biodegradable waste from both households and agriculture sections is emphasized.

As shown in **Figure 2**, only 35% of biomass and biodegradable waste are utilized in bioenergy production, and this will lead to a significant increase at 2.3 TWh (governmental target). Currently, the bioenergy production from biomass and biodegradable waste in Norway is also relatively small (0.5 TWh [10]). This can partly be explained by existing large energy production from other renewable resources, i.e. hydropower [11], which leads to fairly low energy price in general. Also, the limited infrastructure for bioenergy production and high investment are the main obstacles to an increased bioenergy production in Norway. The political willingness is to change the current situation of bioenergy production and establish more bioenergy plants in Norway. However, the governmental subsides and economic incentives for promoting bioenergy production have not been well established yet. In addition, some other institutional and regulative mechanisms should also be considered, i.e. competence enhancement, tax relief for transport utilizing biofuel, lowering gate fee for the delivery of biomass and biodegradable waste for energy production, etc.

In order to provide a better understanding of the bioenergy production from biomass and biodegradable waste, a general model for value chain analysis is first formulated and discussed in this chapter, and a feasibility analysis is then given to discuss the opportunities and challenges of establishing a bioenergy production plant in Northern Norway. The reminder of this chapter is structured as follows. Section 2 gives the definition and treatment methods of the feedstock of bioenergy production: biomass and biodegradable waste. Section 3 formulates a general value chain model of bioenergy production and performs the value chain analysis of bioenergy production. Section 4 presents a feasibility study for establishing bioenergy production plant in northern part of Norway. Section 5 summarizes the chapter and suggests for future studies.

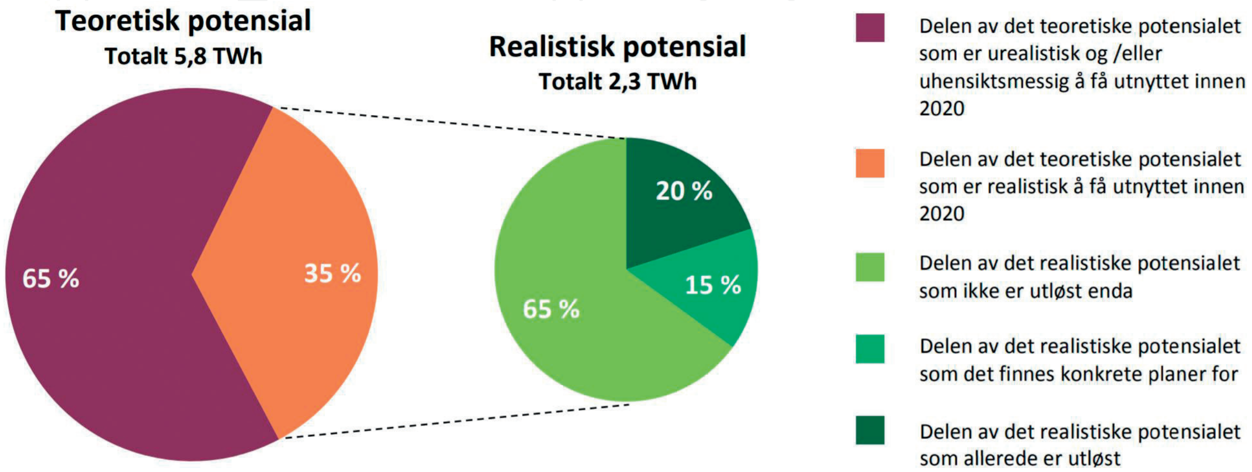


Figure 2. Potential bioenergy production in Norway within 2020 [10].

2. Bioenergy production from biomass and biodegradable waste

2.1. Biomass and biodegradable waste

Biomass is defined in twofold [12]. One is "*the total quantity or weight in a given area or volume*", which emphasizes its essential attribute as organic degradable substances. This definition is on a biological ecological basis. Another is "*organic matter used as a fuel, especially in a power station for the generation of electricity*", and this definition focuses the use of biomass for energy production. Similarly, Cambridge dictionary [13] defines biomass from both biological and engineering perspectives. From biological perspective, the biomass is defined as "*The total mass of living things in a particular area*". Herein, the inherent property of biomass as "living things" is focused. From engineering perspective, the biomass is defined as "*dead plant and animal materials suitable for using as a fuel*", and the property of biomass as a type of fuel is emphasized.

Biodegradable waste is another commonly used term to describe the feedstock of bioenergy production. Biodegradability is referred as the ability to decay naturally and non-harmfully [14]. According to Basel Convention [15], wastes are defined as "*substances or objects, which are disposed of or are intended to be disposed of or are required to be disposed of by provisions of national law*". Viewing from consumers' perspective, EU Directive 2008/98/EC [16] defines waste as "*an object the holder discards, intends to discard or is required to discard*". Based on the definition above, biodegradable waste is the portion of waste that can be decayed by nature.Biomass and biodegradable waste are the most important sources for bioenergy production, which mainly come from five sectors: forestry and timber, agriculture, fishery, waste management and wastewater treatment (**Figure 3**). It is noteworthy that the portion of biomass and biodegradable waste contributed by different sectors may vary dramatically from country to country, and the generation is significantly influenced by seasonality. Therefore, it is necessary to take into account of those variations and uncertainties in forecasting the amount of the feedstock for bioenergy production.

The difference between the two concepts is, compared with biodegradable waste, biomass that specifies a broader domain in which not only organic matters discarded by consumers

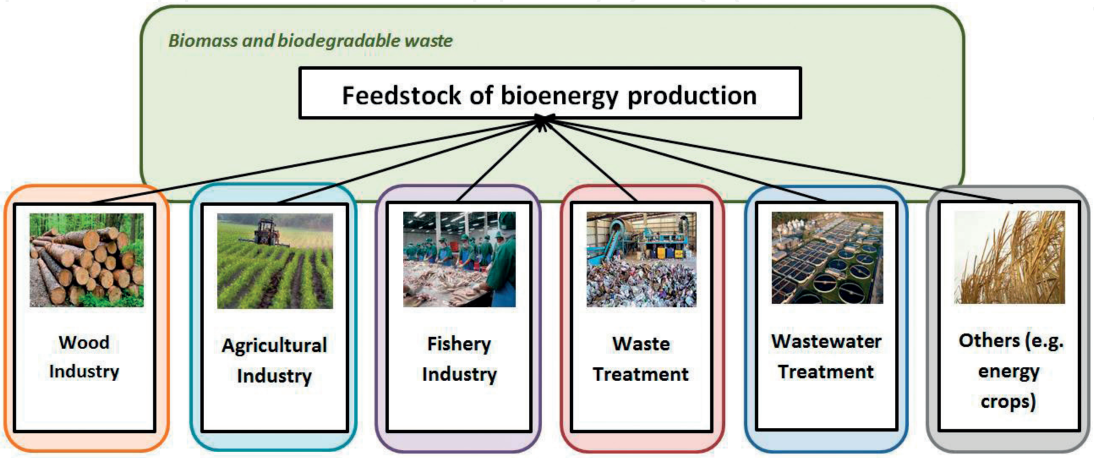


Figure 3. Sources of biomass and biodegradable waste.

but also the ones obtained intentionally for bioenergy production is included (e.g. energy crops). However, those two terms can sometimes be interchangeable when the feedstock of bioenergy production mainly refers to the organic substances that have lost their usefulness value to the consumers, and this applies to the case study presented latter in this chapter.

2.2. Treatment of biomass and biodegradable waste

Based on processing technologies, the treatment of biomass and biodegradable waste can be categorized into four types: direct combustion, thermochemical conversion, biochemical conversion and non-value-added treatment. The first three types are waste-to-energy (WTE) processes aiming to exploit the remaining value of biomass and biodegradable waste, and the last one usually refers to landfill at which the remaining value is eventually lost. Landfill is usually the least expensive but a non-sustainable way for biodegradable waste treatment [17], and the portion of biodegradable waste landfilled has continuously decreasing in Europe due to the rigorous and comprehensive legislations. WTE is the transformation of biomass and biodegradable waste into energy, and it initially specifies the production of power and heat through the combustion of biomass and biodegradable waste [18]. Nevertheless, its meaning has broadened to include other means of bioenergy recovery with the rapid technological development. Bioenergy has been extensively used in different industries, i.e. transport sector, power generation, heating, agriculture and chemistry industry [19]. **Table 1** illustrates the alternative means for bioenergy production and non-value-added treatment of biomass and biodegradable waste.

2.2.1. Direct combustion

Direct combustion has been widely used for over three decades in generating electricity and heat from biomass [20]. The principle is to utilize the heat generated by combustion of biomass for cooking, industrial process, direct home heating [21] or driving the steam power cycle for

Technology	Method	WTE/disposal	Product	Market
Thermochemical conversion	Pyrolysis	WTE	Bio-oil	Transport
	Gasification	WTE	Syngas	Chemistry, transport
Direct combustion	Incineration	WTE	Electricity, heat	Power, heating
Biochemical conversion	Composting	WTE	Fertilizer	Agriculture
	Anaerobic digestion	WTE	Biogas, fertilizer	Transport, agriculture
	MBT	WTE	Biogas, fertilizer	Transport, agriculture
Non-value-added treatment	Landfill	Disposal	N/A	N/A

Table 1. Alternative technologies for bioenergy production and non-value-added treatment of biomass and biodegradable waste.

electricity generation [22]. Due to the high level of moisture content, combustion promoters are usually used in order to improve the conversion efficiency. Coal is the most frequently used promoter, and co-combustion of biomass/biodegradable waste with coal has dominated the bioenergy production market in some countries, i.e. Sweden, Japan, etc. However, environmental challenges, i.e. emission of CO_2, SO_x and NO_x, from the co-combustion process are the major bottleneck for this method for bioenergy recovery [23]. Furthermore, as the common challenge of incineration plant, the flying ash is another pollutant that needs lots of efforts and costs to deal with so that the environmental influence is minimized.

2.2.2. Thermochemical conversion

Thermochemical conversion utilizes constant and high temperature combined with catalysts to convert biomass inside the boiler to biofuel and bioenergy through changing their physical properties and chemical structure [24]. The main technologies of thermochemical conversion of biomass and biodegradable waste include pyrolysis, gasification, liquefaction and torrefaction [25], among which pyrolysis and gasification are considered the most promising ones [26]. Pyrolysis is a fundamental method to transform biomass into crude-like liquid bio-oil [27], and after the chemical decomposition, the liquid bio-oil can be converted to the combustion fuels mainly used for transport and chemical industry [28]. The principle of pyrolysis process is the combination of thermal and chemical decomposition with the help of catalysts at relatively lower temperature (450–600°C) and longer vapor residence time in absence of oxygen for converting the organic substances to liquid bio-oil with charcoal and gases as the by-products [24, 29]. Gasification is another important thermochemical technology that converts different kinds of biomass into syngas. The main composition of syngas is methane, hydrogen, carbon dioxide and carbon monoxide, which are extensively applied in space heating, power generation, transport and chemical industry [30]. Different from pyrolysis, gasification process requires relatively higher temperature (700–1300°C) with the absence or limited oxygen environment in order to optimize the production of syngas [23, 26]. Recently, with the technological development, the probability of biomass and biodegradable waste gasification at lower temperature has also been discussed (e.g. [31]).

2.2.3. Biochemical conversion

Biochemical conversion utilizes biological and chemical processes with the help of aerobic or anaerobic microorganism to transform biomass into biogas and bio-rest, and the main biochemical technologies are composting, anaerobic digestion and mechanical biological treatment (MBT). Composting is an aerobic digestion process and a popular method for the treatment of biomass and biodegradable waste (e.g. Finland). The basic principle is to use biochemical process with the help of aerobic microorganism under open air environment for converting biomass into environmentally friendly bio-rest, which can be used as fertilizer. Anaerobic digestion is the most popular biochemical technology for bioenergy production, and thousands of anaerobic digestion bioenergy production plants have been established all over the world [32]. Through the biochemical decomposition process with the help of anaerobic bacteria at constant temperature in the absence of oxygen, the biomass can be transformed into not only bio-rest but also energy-rich biogas [33]. Biogas is mainly comprised by methane (60%) and carbon dioxide (40%), and it is mainly used as vehicle fuels after cleaned and upgraded [34]. In some cases, aerobic digestion and anaerobic digestion are combined for the treatment of biodegradable waste, e.g. wastewater sludge [35]. MBT combines mechanical pre-treatment and anaerobic digestion. The pre-treatment of biomass through different physical and mechanical processes breaks the physical structure and improves the quality of the input organic substances for anaerobic digestion [36], and the efficiency of bioenergy production is improved as well. Comparing with aerobic composting, both anaerobic digestion and MBT processes have much higher requirement for creating thermostatic and anaerobic environment.

3. Value chain analysis of bioenergy production from biomass and biodegradable waste

3.1. A value chain model for bioenergy production

The concept of value chain was originally proposed by Porter from financial perspective to account the sequential value creation and appreciation through the whole network comprised by different companies and enterprises [37]. This concept is usually accompanied with another word with similar meaning: supply chain (i.e. in [38, 39]). The difference between those two concepts is sometimes negligible especially when the value creation and appreciation process over the material flow are predominately accounted. However, a recent study by Holweg and Helo [40] has explicitly distinguished the two concepts from the perspective of their focuses. Supply chain management focuses on the links and interactions among different companies from the operational level considering strategies, methodologies, design, planning and operation of an efficient and effective multi-stakeholder inner- and/or inter-company network. However, value chain mainly concerns the value-added activities from one company to another within the network and the opportunities and challenges for maximizing the overall value creation and appreciation through the whole network.

The value chain of bioenergy production from biomass and biodegradable waste has been extensively modelled in the literature. Balaman and Selim [41] proposed a biomass-to-energy value chain model and a decision support tool for maximizing the overall profit generated through bioenergy production. A simplified value chain model is developed by Parker et al. [42], and the primary target of the model is to improve the economic value of biofuel production from biomass. An et al. [43] formulated a computational model to optimize the overall profit of a lignocellulosic biofuel value-added chain. Kim et al. [44] developed a four-echelon value chain framework for biofuel production through fast pyrolysis conversion. The maximization of the overall value creation from bioenergy production is focused by Kim et al. [45] and Dal Mas et al. [46]. The maximization of the value creation is sometimes formulated in an opposite way that minimizes the system cost. Chen and Fan [47] formulated a bioethanol production value chain model that applies mixed integer programming for minimizing the overall system cost. Aksoy et al. [48] developed an optimization model for minimizing the transportation cost of bioenergy production from woody biomass and mill waste. The environmental benefits of bioenergy production have been increasingly focused in recent years. A value-added chain of bioenergy production from biomass is modelled by Lam et al. [49], which focuses on the mitigation of carbon footprint of bioenergy production.

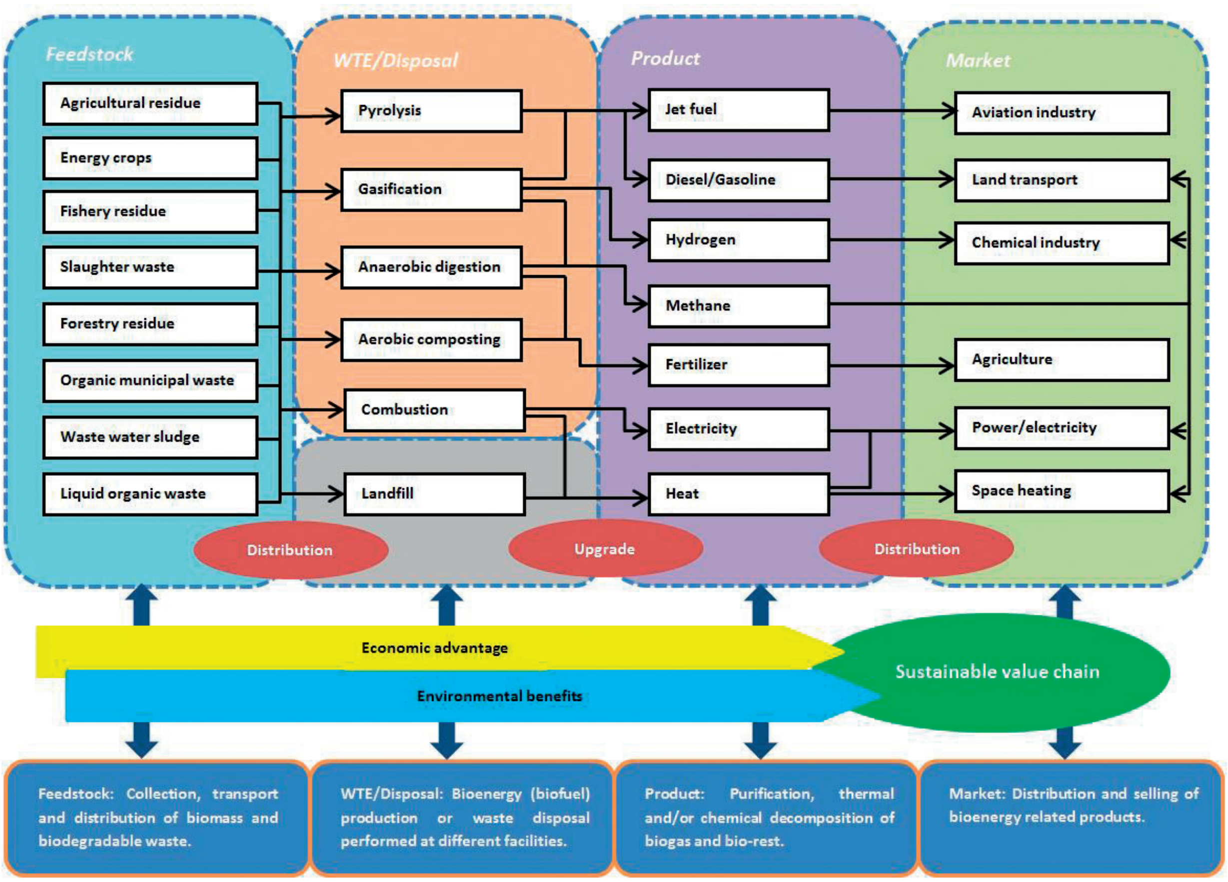


Figure 4. A general value chain model of bioenergy-from-biomass and biodegradable waste.

Bioenergy production from biomass yields economic benefits while reduces waste. However, it is not focused in the literature to account both economic and environmental benefits in the value chain of bioenergy production. In order to fill the literature gap, a general value chain model of bioenergy production from biomass and biodegradable waste is given in **Figure 4**. A typical value-added process of bioenergy production consists of the following activities:

- *Harvesting and collection of biomass and biodegradable waste from different sectors:* The main feedstock of bioenergy production includes agricultural residues, forestry residues, unban woody residues, fishery residues, slaughter wastes, animal manure, biodegradable municipal wastes and wastewater sludge, which are usually collected by different companies and/or public service departments.

- *Intermediate storage and distribution of biomass and biodegradable waste:* Road transport is the most flexible and commonly used way for the distribution of biomass and biodegradable waste; however, other means, i.e., train and ship, are also applicable especially for large amount of biomass and biodegradable waste transported over very long distance due to their relatively low costs.

- *Bioenergy production or proper disposal of biomass and biodegradable waste:* It is the most important value creation process that transforms the "raw materials" into "semi-finished product". The main technologies are gasification, pyrolysis, aerobic composting, anaerobic digestion, direct combustion and landfill.

- *Purification and upgrade of the generated bioenergy:* This step is a critical value-added process that converts the "semi-finished product" into "finished product". The biogas and bio-fuel produced from previous step cannot be directly sent to market due to their complex chemical composition and low efficiency, so thermal and chemical decomposition, purification and upgrade are necessary in this phase. Besides, the model aims at maximizing the value creation of bioenergy production, so the utilization of landfill gas is taken into account in this value chain model.
- *Distribution and sales of the bioenergy as well as other by-products in the market:* This is the final step of the value chain of bioenergy production, where the value creation from the bioenergy production is eventually realized. The biogas, bio-fuel and bio-rest can be used in many different sectors including transport, aviation industry, chemical industry, agriculture, power generation and space heating.

3.2. Value chain analysis of bioenergy production

Value chain analysis has been widely used for investigating, through qualitative and/or quantitative methods, the value-added process in many different fields, i.e. mining industry, fishery industry, aviation industry, dairy industry, catering, production and manufacturing, etc. Conventionally, value chain analysis only emphasizes the value creation and appreciation from financial point of view. However, the increased concern on environmental challenges has led to much more focuses on the "green value-added process" in which not only economic value creation but also environmental value contribution through the entire material flow is accounted (e.g. in [50]). Bioenergy production is a value-added process from both economic and environmental perspectives, so value chain analysis is a reasonable basis for regarding pro et contra for bioenergy production. The value chain of bioenergy production comprises all joints in the flow from materials to products, and it can be analysed in such a way that all important joints are balanced out of a combination of economic and sustainable aspects all the way from cradle to grave.

Value chain analysis of bioenergy production provides decision makers with fundamental basis to divert biomass and biodegradable waste from landfill to WTE process. Previously, the value of biomass and biodegradable waste does not get enough attention, and a large portion is treated through non-value-added method that leads to great potential environmental problems. The model streamlines the value creation and appreciation of bioenergy production from biomass and biodegradable waste, and both economic advantages and environmental benefits are discussed. Bioenergy production takes a different point from waste management perspective to consider biomass as the "raw material" of the value chain and realize the transformation from "waste" to "financial and environmental value". The utilization of biofuel and biogas can dramatically decrease the high dependency on fossil fuels and improve the energy security of a country; further, the nature of self-replenishment of biomass and biodegradable waste makes them become one of the most important renewable energy resources. Besides,

Decision level	Decisions
Strategic decision	• Selection of WTE and treatment technologies • Selection of network configuration: location, capacity, etc. • Selection of potential suppliers and markets
Tactical decision	• Selection of equipment at different facilities • Aggregate production planning • Policy making for supplier and customer management
Operational decision	• Execution of the policies made in previous step • Scheduling and route planning

Table 2. Some strategic, tactical and operational decisions in the planning of a value chain for bioenergy production.

the GHG and hazardous gas emission can be reduced by the utilization of biofuel and biogas as the substitutes of fossil fuels in land transport and aviation industry [51].

The realization of an effective and efficient value-added chain of bioenergy production from biomass and biodegradable waste requires sophisticated decision tools for planning and developing an optimal and robust logistical network, and several strategic, tactical and operational decisions that have to be made are summarized in **Table 2**. In order to provide reliable support for decision-making, great efforts should be spent in the development of theoretical and computational models and decision support systems. Besides, the inherent characteristic of the seasonal availability of biomass and biodegradable waste generation makes the prediction of the feedstock of bioenergy production becoming extremely complicated. Therefore, the aforementioned factors have become the most challenging obstacles for realizing the value-added process of bioenergy production, and inappropriate decisions will hinder the achievement of maximum value creation and appreciation.

4. A value chain and feasibility analysis for establishing bioenergy plants in Northern Norway

4.1. Bioenergy production and bioenergy plants in Norway

The most significant energy consumption in Norway is electricity, which constitutes 88.8% of the total energy consumption in 2012, and it is approximately 17 times higher than the second largest one: petroleum products [52]. The main reason for the high dependency on electrical power is the lower price than other types of energy resources due to the rich reserves of hydropower for electricity generation. Hydroelectric power once contributed more than 99% electricity production in Norway [53], and the situation has not been changed until the latest years when energy production from biomass and biodegradable waste takes a small share from hydroelectric power.

All the Scandinavian countries, such as Denmark, Sweden, Norway and Finland, support the use of renewable energy resources for power generation and space heating, among which Norway has expelled itself as one of the best countries in Europe for renewable energy generation and consumption (58%) due to the high contribution from hydroelectric power [54]. However, the contribution from bioenergy production is extremely insignificant. Furthermore, compared with other Scandinavian countries where bioenergy has already played an important role in power generation, the share of electricity production by biomass and biodegradable waste in Norway is much smaller as shown in **Figure 5**.

The government in Norway has made an ambitious strategic plan for dramatically increasing the bioenergy production by 2020 through policy measures and financial supports [55]. For example, waste regulation has been implemented in Norway since 2009 implementing a ban, which specifies alternative ways for the treatment of biodegradable waste other than landfill. Besides, the forestry and agricultural legislation promote sustainable economic and environmental development in forest management and agriculture industry [53], so bioenergy production from forest and agricultural residues is encouraged. Further, the use of biofuels in land transport to replace fossil fuels is also encouraged in Norway. The road tax charges carbon emission for the vehicles using petroleum and natural gas products, but the cars using biofuels or biogas as the main power are exempt from this charge. In addition, plans for increasing the use of bioenergy for space heating of public and commercial buildings are also under development in order to reduce the fossil fuel consumption for heating.

In Norway, bioenergy production has two characteristics. First, compared with electricity generation, the use of biofuels and biogas in transport sector seems more attractive, because it decreases both the high dependency on fossil fuels and GHG emissions. Besides, Norway

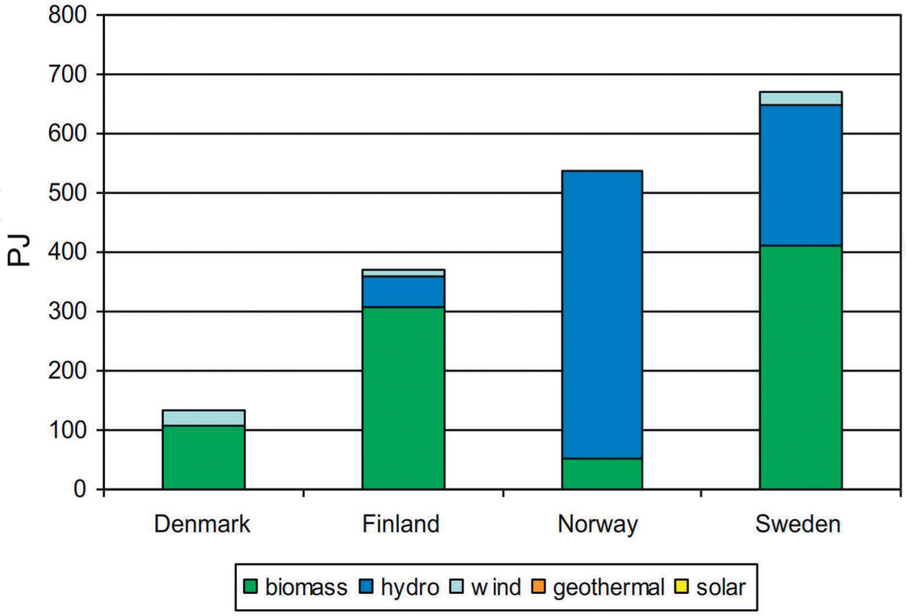
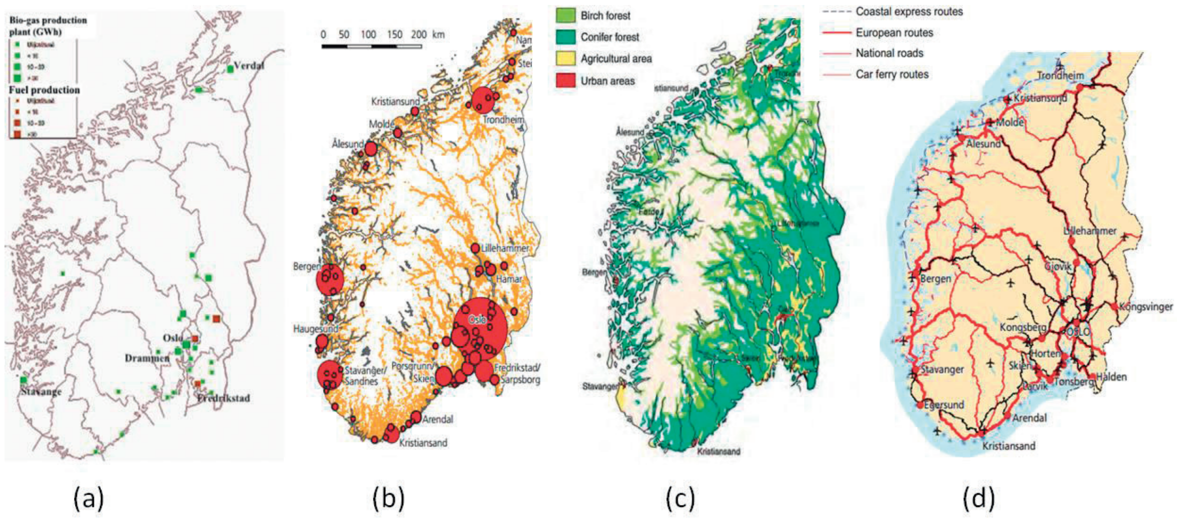


Figure 5. Power generation by sources in Scandinavian countries [54].

implemented the report of biofuels' usage in transport sector from 2014, and it has become one of the most important criteria to assess sustainability in transport sector. Therefore, thermochemical technologies, anaerobic digestion and MBT are widely used methods in Norway for biogas and biofuel production.

Figure 6 illustrates the established biogas and biofuel production plants as well as the demographic distribution, forestry and agricultural areas and road transport network in Norway. Currently, all the established bioenergy production plants are geographically located around the largest cities in the southern and central parts of Norway, and the northernmost bioenergy production plant is located at Verdal (North Trøndelag County). The established biogas and biofuel production plants in Norway have maintained well economic performance and contributed to the mitigation of GHG emissions. The critical success factors for bioenergy production in this region are summarized as follows:

- Dense population, agricultural and industrial clusters provide enough feedstock of biomass and biodegradable waste for bioenergy production.
- Well-developed road transport network provides easy access to the collection and distribution of biomass and biodegradable waste.
- Short distance between the bioenergy plants and collection points of biomass and biodegradable waste reduces the transportation and logistics cost.
- Governmental support for developing biogas and biofuel market, i.e. biogas used as the main fuel for the public transport in Fredrikstad, tax relief for biogas and biofuel in transport sector [53].
- Incentives for bioenergy production from biomass and biodegradable waste.



(a) (b) (c) (d)

Figure 6. (a) Established biogas and biofuel production plants in Norway; (b) demographic distribution of southern and central parts of Norway; (c) forestry and agricultural industry in southern and central parts of Norway; and (d) road transport network of southern and central parts of Norway [11, 52].

The other characteristic of bioenergy production in Norway is the feedstock mainly comes from forestry/wood industry and waste management. **Figure 7** illustrates the sources of biomass and biodegradable waste for bioenergy production in Nordic countries. As shown in the figure, black liquor from chemical industry and wood residues from forestry industry are the most important resources for bioenergy production in Sweden and Finland, while the feedstock for bioenergy production in Norway and Denmark is mainly from waste management sector and forestry industry. Utilization of wood and forestry residues has been well-developed in Norway, and previous studies have discussed the policy structure [56], impact [57] and future potential [58] of bioenergy production from forestry biomass and waste. Besides, it is also noteworthy that energy crops, i.e. poplar, reed canary grass, willow, etc. [59], are not commercially cultivated in Norway, and the portion of bioenergy production from energy crops in the other Scandinavian countries is small as well. The main reason is that the long winter and cold climate in Scandinavian countries make it becoming economically unaffordable for cultivation of energy crops for bioenergy production in this area.

4.2. A feasibility study of bioenergy production in Nordland county

Bioenergy production in Northern Norway has been focused for many years. However, the negotiation between different stakeholders has been difficult reaching an implementation plan due to the conflicting interests involved. Earlier, the locations of landfill and composting plant were focused due to the consideration of the costs for waste collection and environmental risks of treatment facilities of biodegradable waste. Recently, the treatment plants have been equipped with closable ports, ventilation system, air cleaning system as well as other upgrades, which tremendously reduce the negative impact on the environment, and the focus on the energy recovery of biodegradable waste has been increasingly discussed.

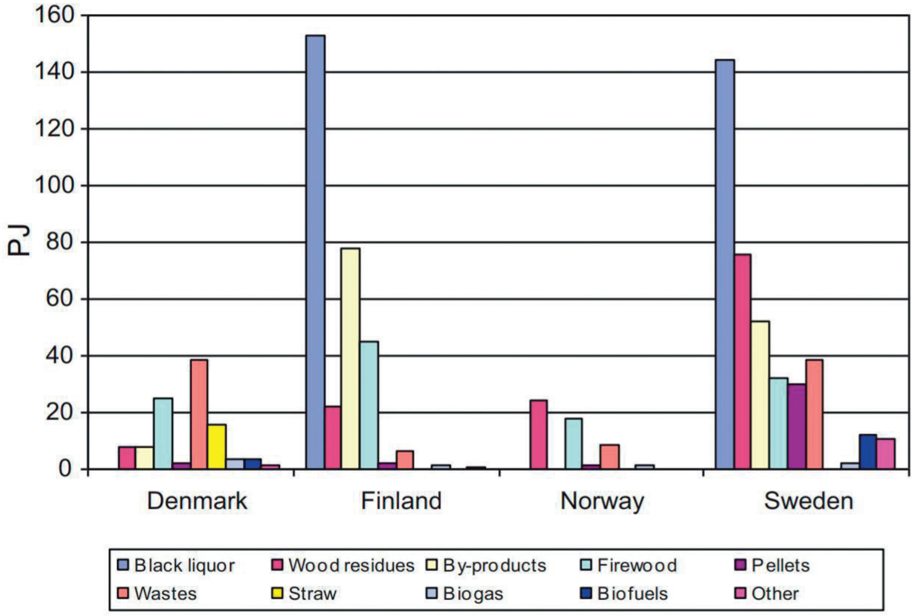


Figure 7. Bioenergy production by sources in Nordic countries [54].

In order to promote bioenergy production from biomass and biodegradable waste, Nordland County has drafted an initial plan for establishing a bioenergy plant at the costal-town Leknes. Leknes is the geographic centre of the famous Lofoten archipelago, and the close proximity to local agricultural areas, fishery and livestock industry is the main reason for the strategic decision of plant location. Besides, Leknes also has long-term experience in aerobic technologies, and the biomass and biodegradable waste generated at this region are treated at the composting plant. The upgrade of the aerobic composting plant to a MBT plant for producing biogas has been discussed for several years, and the strongest support is from local agriculture and livestock industry.

Leknes is one of the largest agricultural municipalities in Nordland County, and the meat production from poultry and livestock is on a large scale. The treatment of animal's manure is one of the most challenges in this area. Traditionally, the animal's manure is stored during winter time in barn and used as fertilizer for pasture grass production, but the emissions of methane and other hazardous gases from animal's manure are harmful to the environment. The planned MBT plant can effectively resolve this problem through converting the animal's manure into biogas and bio-rest, which can be used as vehicle fuel and fertilizer, so the plan is welcomed by local agriculture and livestock industry. Another supporter for bioenergy production from biodegradable waste is the local waste management company: LAS. Currently, LAS operates a landfill and a composting plant, and the anaerobic digestion facility planned in Leknes will be an attractive alternative for the treatment of biodegradable waste from LAS.

Figure 8 illustrates the value-added process of bioenergy production. The feedstock in this area is mainly from agriculture residues, livestock residues, fishery residues and municipal waste; however, biomass from forestry industry is not included in the current plan. The technology applied for bioenergy production in Leknes is MBT, and the main products are biogas and bio-rest. The biogas can be used as the fuels at land transport sector, and the bio-rest can be used as fertilizer for agriculture industry. Both biogas and bio-rest can either be used locally or sold in domestic/international markets.

The bioenergy production plant in Leknes aims at providing a sustainable solution in dealing with biomass and biodegradable waste from the municipalities in Nordland County. The most important factor of bioenergy production is to maintain economy of scale, so knowledge

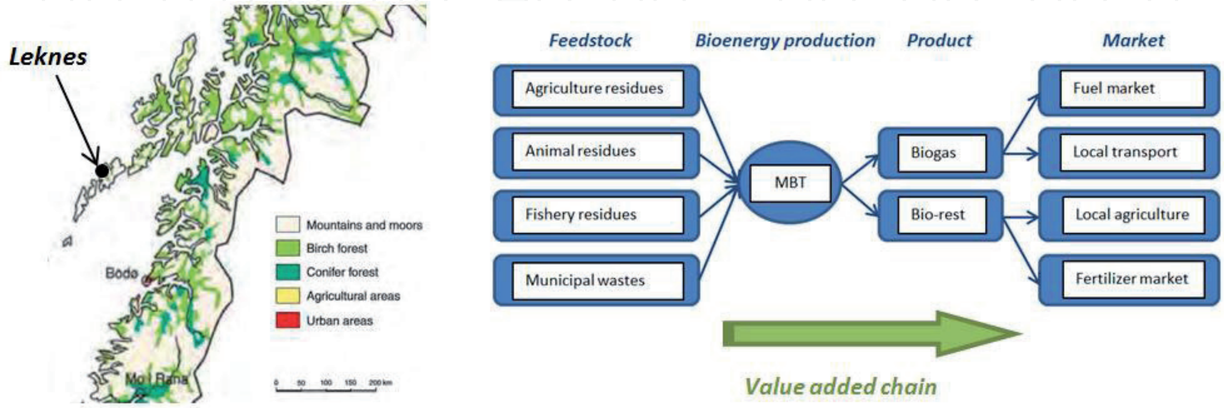


Figure 8. Value chain architecture of bioenergy production plant at Leknes [11, 52].

Biodegradable waste	Estimated biogas output (m^3/year)(4)	Average factor(4)	Total biogas output (m^3/year)	Conversion factor (KWh/ton)(4)	Total estimated energy output (GWh)
BMW(1)	204	180	2,340,000	1120	14.5
BWS(2)	93	102	142,800	444	0.62
AM(3)	19	19	95,000	190	0.95
Sum	N/A	N/A	2,577,800	N/A	16.3

(1)BMW: biodegradable municipal waste.

(2)BWS: biodegradable waste from slaughterhouse.

(3)AM: animal's manure.

(4)Basic data from Refs. [8, 63, 64].

Table 3. Estimated output amounts of biogas and bioenergy.

of annual generation of biomass and biodegradable waste is of importance. Estimation of the annual amount of three types of biodegradable waste is presented as follows:

1. Biodegradable municipal waste collected by regional waste management companies: 13,000 ton/year.
2. Biodegradable waste from slaughterhouse: 1400 tons/year.
3. Animal's manure from livestock industry: 5000 tons/year.

Calculation of the output of bioenergy production based on input amount provides valuable criteria for value chain analysis. Previous studies have formulated different models for the calculation of biogas output from different types of feedstock. Calculation in this chapter is based on the established models for biodegradable municipal waste and livestock residues from Norway [8], Sweden [60] and Denmark [61]. **Table 3** gives the estimated output of biogas from the three types of feedstock. The estimated output amount may be different from the actual amount, and this is due to the following reasons:

- The calculation of the outputs from the three types of biodegradable waste is conducted through the combination of different literatures. However, as a general rule, the biogas output in reality is usually lower than the estimated value.
- It is a common situation that different types of biomass are mixed in the digester for anaerobic digestion, and this will lead to different output amount with the separate digestion that estimated in the table. It is therefore impossible to foresee the exact output due to the biochemical decomposition of protein, carbohydrates, lipid differs and other substrates.
- Animal's manure has the least conversion efficiency, but its presence has great meaning for the conversion of mixed biomass and biodegradable waste due to the content of bacteria, nourishment and trace elements, which provide a stabilizing effect for the microbial digestion in the reactor tank. Researches on the optimization of biogas production have revealed that

compound mixtures of different substrates result in a microbial society with a larger diversity and are more stable [62], and that counts for an optimistic view of the calculated output.

Environmental challenges in high north arctic regions have been attracted much more focuses due to the potentially severe consequences such as melting glaciers and sea-level rise caused by global warming. GHG emissions have been proved to be the most important driving force for the global warming and climate change, and it has more influences on the vulnerable eco-environment. Thus, the environmental impact of bioenergy production is assessed by GHG emissions. Two types of GHG emissions are estimated in this chapter, one is the emissions of methane from stored animal's manure in livestock industry, and the other is the CO_2 emissions from the transportation to the MBT plant at Leknes.

The storage of animal's manure in winter not only occupies great space but also releases a large amount of methane. The treatment of animal's manure through bioenergy production can effectively resolve this problem. From the national perspective, Norwegian strategic document for bioenergy development estimates that the overall amount of animal's manure from livestock industry for potential bioenergy production in Norway is approximately 3.92 million tons, and this will lead to 305,000 tons CO_2-equivalent reduction of GHG emissions [10]. The amount of different animals in local livestock industry is given by the Farmer's Interest Organization at Lofoten region. Besides, we also presupposed an input amount of 5000 tons of animal's manure to a co-substrate-mixture at the bioenergy production plant. **Table 4** illustrates the annual emissions of methane from the animal's manure by sources. Based on the method provided in the governmental calculation, an overall 0.39 tons CO_2-equivalent reduction of methane emissions from local livestock industry can be estimated. Besides, the calculation also implies a reduction of fertilizer for pasture grass production; however, this can also be solved by utilizing the bio-rest from bioenergy production at Leknes. Development for utilizing wet bio-rest in agriculture has recently been proved to be a good fertilizer [64–66], and the close distance from local agriculture and livestock industry to the planned location of the MBT plant is another advantage for the utilization of bio-rest.

Animal	Amounts(1)	Individual methane emission factor (ton/animal/year)(2)	Total emission of methane (ton/year)
Cow (milk)	830	0.018	14.9
Cow (meat)	2100	0.0027	5.67
Hen	2600	0.0009	2.34
Pig	80	0.0071	0.568
Sheep	6800	0.0002	1.36
Goat	975	0.00012	0.117
Horse	69	0.00295	0.204
Sum			25.2

(1)Data provided from Farmer's Interest Organization, Lofoten region.

(2)Basic data from statistical yearbook of Norway [52].

Table 4. Emissions of methane from stored animal's manure.

GHG emissions associated with the transportation of biomass and biodegradable waste to Leknes are another important problem when the bioenergy production network is designed. In Nordland County, four regional waste management companies are involved in the collection, transportation and treatment of biodegradable waste in different municipalities: HRS, RENO VEST, IRIS and LAS. Currently, RENO VEST and LAS send their waste to Leknes for aerobic composting, and the organic waste collected at Narvik municipality is treated at the incineration plant at Kiruna in northern Sweden. Bodø municipality has its own composting plant for dealing with biodegradable waste. Obviously, both aerobic digestion and direct combustion are less sustainable than bioenergy production through MBT, so the planned MBT plant at Leknes becomes a suitable alternative for HRS and IRIS.

Table 5 presents the annual generation of biodegradable waste at different municipalities in Nordland County, and the distance from each municipality to Leknes is also given in this table. As shown in the table, transportation of small amount of biodegradable waste over long distance is necessary when the MBT plant is located at Leknes, and this will lose the advantage of economy of scale and increase GHG emissions. However, it is also the situation in today’s waste management system. For example, the biodegradable waste collected at Narvik municipality travels 178 km to Kiruna for incineration. Compared with today’s situation, only the transportation of biodegradable waste from Narvik and Bodø to Leknes will increase GHG emissions. **Table 6** illustrates the estimation of CO_2 emissions from the transportation of biodegradable waste to Leknes. The estimated CO_2 emissions are calculated based on the information provided by the waste management companies, which include the monthly generation of biodegradable waste in each community and the unit fuel consumption of waste collection and further distribution. Compared with the current waste management system, the CO_2 emissions of biomass and biodegradable waste transportation of the planned bioenergy production system will be increased by 19.3%.

Although it is difficult to formulate the complete value-added process of bioenergy production, we can still see a large potential of a sustainable solution for both energy production and waste management in Northern Norway. However, decisions must be made based on the consideration and justification of both benefits and challenges, and the interests of different stakeholders within the value chain of bioenergy production should also be taken into account. **Table 7** summarizes the opportunities and challenges of bioenergy production in Nordland County. As shown in the table, bioenergy production from biomass and biodegradable waste will deliver a great amount of biofuels and fertilizer to the market; besides, it will decrease GHG emissions as well as other environmental impacts from local agriculture, livestock industry and waste management. However, the costs and CO_2 emissions of the transportation in the overall bioenergy production network will be increased, and the operating costs of the MBT plant are higher in the cold regions due to more energy consumption for maintaining a constant temperature for anaerobic digestion. Further, there are uncertainties about the potential markets for biofuels and fertilizer, and the cost and CO_2 emission will be increased for the transportation of them to potential markets.

In order to resolve those challenges, policy support must be first formulated accordingly by the government so that the value added through the bioenergy production can be shared by all the stakeholders within the value chain. For example, governmental incentives or tax relief

Waste management company	Estimated waste (ton/year)	Distance to Leknes (km)(3)
Leknes (LAS)(1)	3400	0
Bodø (IRIS)(2)	5000	160(4)
Harstad (HRS)(2)	2300	263
Sortland (RENO VEST)(2)	2200	183
Narvik (HRS)(2)	2200	305

(1)Including the biodegradable waste from slaughterhouse.
(2)Data given by relevant waste management companies.
(3)Calculated on Google map.
(4)Including ferry boat transport.

Table 5. Generation of biodegradable waste in Nordland County.

Unit fuel consumption (L/km)	Annual transport distance (km/year)	Fuel consumption (L/year)	CO_2 emission (ton/year)(1)
LAS (local area) 0.58	24,000	13,920	37.4
RENO VEST 0.42	38,896	16,336	44
HRS, Harstad 0.48	62,660	30,077	39
HRS, Narvik 0.48	64,480	30,950	40
IRIS, Bodø 0.48	21,538	10,333	13
Total	211,564	101,616	173.4

(1)Calculated based upon Energilink [67].

Table 6. Estimated fuel consumption and CO_2 emissions from the transportation.

Opportunities	Challenges
• Large amount production of biofuels • Production of bio-rest/fertilizer • Increased use of biofuels in transport • Less GHG emissions from agriculture, livestock industry and waste treatment • Less environmental impact	• Increased costs for the transportation of biodegradable waste • Increased CO_2 emission from the transportation of biodegradable waste • Increased investment on bioenergy production in cold climate • Uncertain market demands • Cost and CO_2 emission related to the distribution of biofuels and bio-rest to potential market

Table 7. Opportunities and challenges of bioenergy production in Nordland County.

should be given to HRS and IRIS to compensate their increased transportation cost to deliver the biodegradable waste to Leknes, and this may also be achieved through implementing a lower entrance fee of the MBT plant. Besides, the successful example of using biofuels in the public transport sector in Southern Norway is also applicable for Nordland County, and the upgrade of buses for using biofuels should be subsidized by the local government. Further, the incentives or lower purchase price should also be given to the agriculture and pasture grass production in order to promote the local use of bio-fertilizer, which will tremendously decrease the cost and GHG emissions for delivering the bio-fertilizer to remote markets.

5. Conclusion

During the past decades, the concerns of the depletion of fossil fuels and global warming caused by excess GHG emissions have become the most important driving force for the development and utilization of renewable energy resources. The successful experiences from the EU-28 have proved that bioenergy production from biomass and biodegradable waste is the most reliable and promising solution in today's renewable energy market. This chapter studies bioenergy production from the perspective of value chain analysis. The method of value chain analysis has been developed for over three decades and extensively applied in analysing the value-added process of many different industries. In this chapter, a theoretical architecture for value chain analysis of bioenergy production from biomass and biodegradable waste is first formulated for streamlining the value-added activities in the bioenergy production network. In order to give a deep insight of the developed value chain model, we investigated the current situation of bioenergy production in Norway and compared that with other Nordic countries. The feasibility study for establishing a bioenergy production plant in Nordland County, which is located in the northern part of Norway, is also performed.

The value chain analysis of bioenergy production from biomass and biodegradable waste in Nordland County estimates both the potential amount of bioenergy output and the environmental impact, and suggestions for overcoming the challenges of bioenergy production are also given in this section. In order to better achieve the value-added process in bioenergy production in Nordland County, future studies are suggested from three aspects. First, information from other local industries should be investigated so that a complete value chain of bioenergy production can be formulated. Second, forestry residues are very important feedstock for bioenergy production in other places; however, it is not included in current plan for bioenergy production. Thus, further studies with inclusion of forestry waste as the feedstock of the MBT plant at Leknes should be carried out. Third, decision support tools for optimal design of integrated network for biodegradable waste transportation should be developed in order to balance both transportation costs and GHG emissions in an optimal manner.

Acknowledgements

This project is supported by the Norwegian Research Council/VRI-Nordland (Commitment 2012-0446) under strategy to promote renewable energy production in Nordland County. The article processing charge is financially supported by the Open Access Fund from UiT—The Arctic University of Norway.

Conflict of interest

The authors declare no conflict of interest.

Author details

Hao Yu[1]*, Elisabeth Román[2] and Wei Deng Solvang[1]

*Address all correspondence to: hao.yu@uit.no

1 Department of Industrial Engineering, UiT—The Arctic University of Norway, Narvik, Norway

2 Department of Building, Energy and Material Technology, UiT—The Arctic University of Norway, Narvik, Norway

References

[1] European Environmental Agency (EEA) [Internet]. 2017. Available from: http://www.eea.europa.eu/data-and-maps/indicators/renewable-primary-energy-consumption-3/assessment [Accessed: Oct 29, 2017]

[2] Shafiee S, Topal E. When will fossil fuel reserves be diminished. Energy Policy. 2009;**37**:181-189. DOI: 10.1016/j.enpol.2008.08.016

[3] Legget LMW, Ball DA. The implication for climate change and peak fossil fuel oft he continuation of the current trend in wind and solar energy production. Energy Policy. 2012;**41**:610-617. DOI: 10.1016/j.enpol.2011.11.022

[4] Akorede MF, Hizam H, Ab Kadir MZA, Aris I, Buba SD. Mitigating the anthropogenic global warming in the electric power industry. Renewable and Sustainable Energy Reviews. 2012;**16**:2747-2761. DOI: 10.1016/j.rser.2012.02.037

[5] Vavrova K, Knapek J, Weger J. Modeling of biomass potential from agricultural land for energy utilization using high resolution spatial data with regard to food security scenarios. Renewable and Sustainable Energy Reviews. 2014;**35**:436-444. DOI: 10.1016/j.rser.2014.04.008

[6] Council Directive 1999/31/EC [Internet]. 2017. Available from: http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:31999L0031 [Accessed: Oct 29, 2017]

[7] Directive 2001/77/EC [Internet]. 2017. Available from: http://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX:32001L0077 [Accessed: Oct 29, 2017]

[8] Directive 2009/28/EC [Internet]. 2017. Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=Oj:L:2009:140:0016:0062:en:PDF [Accessed: Oct 29, 2017]

[9] Meld.St. nr 21(2011-2012). Norsk klimapolitikk. Oslo: Miljøverndepartementet [Internet]. 2017. Available from: https://www.regjeringen.no/nb/dokumenter/meld-st-21-2011-2012/id679374/ [Accessed: Oct 20, 2017]

[10] Klima-og forurensningsdirektoratet (2013) Underlagsmateriale til tverrsektoriell [Internet]. 2017. Available from: biogass-strategi http://www.miljodirektoratet.no/old/klif/publikasjoner/3020/ta3020.pdf [Accessed: Oct 29, 2017]

[11] Solvang WD, Roman E, Yu H, Mustafa MY, A decision support system for establishing a waste treatment plant for recycling organic waste into bio-energy in Northern Norway. In: Proceeding of IEEE International Conference on Cognitive Infocommunications, Budapest, Hungary: IEEE. 2013. pp: 659-664. DOI: 10.1109/CogInfoCom.2013.6719184

[12] Oxford Dictionaries [Internet]. 2017. Available from: http://www.oxforddictionaries.com/definition/english/biomass?searchDictCode=all [Accessed: Oct 29, 2017]

[13] Cambridge Dictionaries Online [Internet]. 2017. Available from: http://dictionary.cambridge.org/dictionary/british/biomass [Accessed: Oct 29, 2017]

[14] Cambridge Dictionaries Online [Internet]. 2017. http://dictionary.cambridge.org/dictionary/british/biodegradable [Accessed: Oct 29, 2017]

[15] Basel Convention [Internet]. 2017. Available from: http://www.basel.int/Portals/4/Basel%20Convention/docs/text/BaselConventionText-e.pdf [Accessed: Oct 29, 2017]

[16] Directive 2008/98/EC [Internet]. 2017. Available from: http://ec.europa.eu/environment/waste/framework/pdf/guidance_doc.pdf [Accessed: Oct 29, 2017]

[17] Yu H, Solvang WD, Yuan S, Yang Y. A decision aided system for sustainable waste management. Intelligent Decision Technologies. 2015;**9**:29-40. DOI: 10.3233/IDT-140203

[18] Pavlas M, Tous M, Bebar L, Stehlik P. Waste to energy – An evaluation of the environmental impact. Applied Thermal Engineering. 2010;**30**:2326-2332. DOI: 10.1016/j.applthermaleng.2009.10.019

[19] Demirbas A. Biomass resource facilities and biomass conversion processing for fuels and chemicals. Energy Conversion and Management. 2001;**42**:1357-1378. DOI: 10.1016/S0196-8904(00)00137-0

[20] De Koning HW, Smith KR, Last JM. Biomass fuel combustion and health. Bulletin of the World Health Organization. 1985;**63**(1):11-26

[21] Brauer M, Bartlett K, Regalado-Pineda J, Perez-Padilla R. Assessment of particulate concentrations from domestic biomass combustion in rural Mexico. Environmental Science & Technology. 1995;**30**(1):104-109. DOI: 10.1021/es9501272

[22] Van den Broek R, Faaij A, Wan Wijk A. Biomass combustion for power generation. Biomass and Bioenergy. 1996;**11**(4):271-281. DOI: 10.1016/0961-9534(96)00033-5

[23] Baxter L. Biomass-coal co-combustion: Opportunity for affordable renewable energy. Fuel. 2005;**84**:1295-1302. DOI: 10.1016/j.fuel.2004.09.023

[24] Yue D, You F, Snyder SW. Biomass-to-bioenergy and biofuel supply chain optimization: Overview, key issues and challenges. Computers and Chemical Engineering. 2014;**66**:36-56. DOI: 10.1016/j.compchemeng.2013.11.016

[25] Chen WH, Lin BJ, Huang MY, Chang JS. Thermochemical conversion of microalgal biomass into biofuels: A review. Bioresource Technology. 2015;**184**:314-327. DOI: 10.1016/j.biortech.2014.11.050

[26] Bahng MK, Mukarakate C, Robichaud DJ, Nimlos MR. Current technologies for analysis of biomass thermochemical processing: A review. Analytica Chimica Acta. 2009;**651**:117-138. DOI: 10.1016/j.aca.2009.08.016

[27] Demirbas A. Yields of oil products from thermochemical biomass conversion process. Energy Conversion and Management. 1998;**39**:685-690. DOI: 10.1016/S0196-8904(97)00047-2

[28] Yang H, Yao J, Chen G, Ma W, Yan B, Qi Y. Overview of upgrading of pyrolysis oil of biomass. Energy Procedia. 2014;**61**:1306-1309. DOI: 10.1016/j.egypro.2014.11.1087

[29] Bridgwater AV. Review of fast pyrolysis of biomass and product upgrading. Biomass and Bioenergy. 2012;**38**:68-94. DOI: 10.1016/j.biombioe.2011.01.048

[30] Heidenreich S, Foscolo PU. New concepts in biomass gasification. Progress in Energy and Combustion Science. 2015;**46**:72-95. DOI: 10.1016/j.pecs.2014.06.002

[31] Ravaghi-Ardebili Z, Manenti F, Corbetta M, Pirola C, Ranzi E. Biomass gasification using low-temperature solar-driven steam supply. Renewable Energy. 2015;**74**:671-680. DOI: 10.1016/j.renene.2014.07.021

[32] Sawatdeenarunat C, Surendra KC, Takara D, Oechsner H, Khanal SK. Anaerobic digestion of lignocellulosic biomass: Challenges and opportunities. Bioresource Technology. 2015;**178**:178-186. DOI: 10.1016/j.biortech.2014.09.103

[33] Weiland P. Biogas production: Current state and perspectives. Applied Microbiology and Biotechnology. 2010;**85**:849-860. DOI: 10.1007/s00253-009-2246-7

[34] Moghaddam EA, Ahlgren S, Hulteberg C, Nordberg A. Energy balance and global warming potential of biogas-based fuels from a life cycle perspective. Fuel Processing Technology. 2015;**132**:74-82. DOI: 10.1016/j.fuproc.2014.12.014

[35] Novak JT, Banjade S, Murthy SN. Combined anaerobic and aerobic digestion for increased solids reduction and nitrogen removal. Water Research. 2011;**45**:618-624. DOI: 10.1016/j.watres.2010.08.014

[36] Agbor VB, Cicek N, Sparling R, Berlin A, Levin DB. Biomass pretreatment: Fundamentals toward application. Biotechnology Advances. 2011;**29**:675-685. DOI: 10.1016/j.biotechadv.2011.05.005

[37] Porter ME. Competitive Advantage: Creating and Sustaining Superior Performance. New York: The Free Press, Macmillan Publishing; 1985

[38] Cox A. Power, value and supply chain management. Supply Chain Management: An International Journal. 1999;**4**(4):167-175. DOI: 10.1108/13598549910284480

[39] Tan KC. A framework of supply chain management literature. European Journal of Purchasing & Supply Management. 2011;**7**(1):39-48. DOI: 10.1016/S0969-7012(00)00020-4

[40] Holweg M, Helo P. Defining value chain architectures: Linking strategic value creation to operational supply chain design. International Journal of Production Economics. 2014;**147**:230-238. DOI: 10.1016/j.ijpe.2013.06.015

[41] Balaman SY, Selim H. A fuzzy multiobjective linear programming model for design and management of anaerobic digestion based bioenergy supply chains. Energy. 2014;**74**:928-940. DOI: 10.1016/j.energy.2014.07.073

[42] Parker N, Tittmann P, Hart Q, Nelson R, Skog K, Schmidt A, Gray E, Jenkins B. Development of a biorefinery optimized biofuel supply curve for the western United States. Biomass & Bioenergy. 2010;**34**:1597-1607. DOI: 10.1016/j.biombioe.2010.06.007

[43] An H, Wilhelm WE, Searcy SW. A mathematical model to design a lignocellulosic biofuel supply chain system with a case study based on a region in Central Texas. Bioresource Technology. 2011;**102**:7860-7870. DOI: 10.1016/j.biortech.2011.05.060

[44] Kim J, Realff MJ, Lee JH. Optimal design and global sensitivity analysis of biomass supply chain networks for biofuels under uncertainty. Computers and Chemical Engineering. 2011;**35**:1738-1751. DOI: 10.1016/j.compchemeng.2011.02.008

[45] Kim J, Realff MJ, Lee JH, Whittaker C, Furtner L. Design of biomass processing network for biofuel production using an MILP model. Biomass & Bioenergy. 2011;**35**:853-871. DOI: 10.1016/j.biombioe.2010.11.008

[46] Dal Mas M, Giarola S, Zamboni A. Capacity planning and financial optimization of the bioethanol supply chain under price uncertainty. Computer Aided Chemical Engineering. 2010;**28**:97-102. DOI: 10.1016/S1570-7946(10)28017-3

[47] Chen CW, Fan Y. Bioethanol supply chain system planning under supply and demand uncertainties. Transportation Research Part E. 2012;**48**:150-164. DOI: 10.1016/j.tre.2011.08.004

[48] Aksoy B, Cullinan H, Webster D, Gue K, Sukumaran S, Eden M, Sammons N Jr. Woody biomass and mill waste utilization opportunities in Alabama: Transportation cost minimization, optimum facility location, economic feasibility, and impact. Environmental Progress & Sustainable Energy. 2011;**30**(4):720-732. DOI: 10.1002/ep.10501

[49] Lam HL, Varbanov P, Klemes J. Minimising carbon footprint of regional biomass supply chains. Resource, Conservation and Recycling. 2010;**54**:303-309. DOI: 10.1016/j.resconrec.2009.03.009

[50] Darmawan MA, Putra MPIF, Wiguna B. Value chain analysis for green productivity improvement in the natural rubber supply chain: A case study. Journal of Cleaner Production. 2014;**85**:201-211. DOI: 10.1016/j.jclepro.2014.01.098

[51] Vimmerstedt LJ, Bush B, Peterson S. Ethanol distribution, dispensing, and use: Analysis of a portion of the biomass-to-biofuels supply chain using system dynamics. PLoS One. 2012;**7**(5):e35082. DOI: 10.1371/journal.pone.0035082

[52] Statistical yearbook of Norway 2013 [Internet]. 2013. Available from: http://www.ssb.no/en/befolkning/artikler-og-publikasjoner/statistical-yearbook-of-norway-2013 [Accessed: Oct 20, 2017]

[53] Country policy assessment report on bioenergy: Norway [Internet]. 2015. Available from: http://www.skogoglandskap.no/publikasjon/country_policy_assessment_report_on_bioenergy_norway/content3_view [Accessed: Oct 20, 2017]

[54] Scarlat N, Dallemand JF, Skjelhaugen OJ, Asplund D, Nesheim L. An overview of the biomass resource potential of Norway for bioenergy use. Renewable and Sustainable Energy Review. 2011;**15**:3388-3398. DOI: 10.1016/j.rser.2011.04.028

[55] Sjolie HK, Tromborg E, Solberg B, Bolkesjo TF. Effects and costs of policies to increase bioenergy use and reduce GHG emissions from heating in Norway. Forest Policy and Economics. 2010;**12**:57-66. DOI: 10.1016/j.forpol.2009.08.011

[56] Tromborg E, Bolkesjo TF, Solberg B. Impact of policy means for increased use of forest-based bioenergy in Norway – A spatial partial equilibrium analysis. Energy Policy. 2007;**35**:5980-5990. DOI: 10.1016/j.enpol.2007.08.004

[57] Tromborg E, Solberg B. Forest sector impacts of the increased use of wood in energy production in Norway. Forest Policy and Economics. 2010;**12**:39-47. DOI: 10.1016/j.forpol.2009.09.011

[58] Tromborg E, Bolkesjo TF, Solberg B. Biomass market and trade in Norway: Statues and future prospects. Biomass and Bioenergy. 2008;**32**:660-671. DOI: 10.1016/j.biombioe.2008.02.022

[59] MH S, Huang CH, Li WY, Tso CT, Lur HS. Water footprint analysis of bioethanol energy crops in Taiwan. Journal of Cleaner Production. 2015;**88**:132-138. DOI: 10.1016/j.jclepro.2014.06.020

[60] Lemvigbiogas [Internet]. 2015. Available from: http://lemvigbiogas.com [Accessed: Oct 20, 2017]

[61] Bioforsk rapport: Biogass kunnskapsstatus og forskningsbehov [Internet]. 2015. Available from: file:///C:/Users/Admin/Downloads/Biogasskunnskapsstatusogforskningsbehov2010.pdf [Accessed: Oct 20, 2017]

[62] Oversendelse av forslag til endring av produktforskriften - innføring av bærekraftskriterier og rapportering av biodrivstoff og flytende biodrivstoff [Internet]. 2015. Available from: http://www.miljodirektoratet.no/old/klif/nyheter/dokumenter/Brev_MD_baerekraftskriterier_rapportering_biodrivstoff.pdf [Accessed: Oct 20, 2017]

[63] Themelis NJ, Ulloa PA. Methane generation in landfills. Renewable Energy. 2007;**32**(7):1243-1257. DOI: 10.1016/j.renene.2006.04.020

[64] Mangwandi C, Liu JT, Albadarin AB, Allen SJ, Walker GM. Alternative method for producing organic fertiliser from anaerobic digestion liquor and limestone powder: High shear wet granulation. Powder Technology. 2013;**223**:245-254. DOI: 10.1016/j.powtec.2012.09.017

[65] Chong C, Purvis P, Lumis G, Holbein BE, Voroney RP, Zhou H, Liu HW, Alam MZ. Using mushroom farm and anaerobic digestion wastewaters as supplemental fertilizer sources for growing container nursery stock in a closed system. Bioresource Technology. 2008;**99**:2050-2060. DOI: 10.1016/j.biortech.2007.02.047

[66] Vaneeckhaute C, Meer E, Michels E, Ghekiere G, Accoe F, Tack FMG. Closing the nutrient cycle by using bio-digestion waste derivatives as synthetic fertilizer substitutes: A field experiment. Biomass and Bioenergy. 2013;**55**:175-189. DOI: 10.1016/j.biombioe.2013.01.032

[67] Energilink [Internet]. 2017. Available from: www.energilink.no [Accessed: Oct 26, 2017]