Sustainable use of Baltic Sea natural resources based on ecological engineering and biogas production

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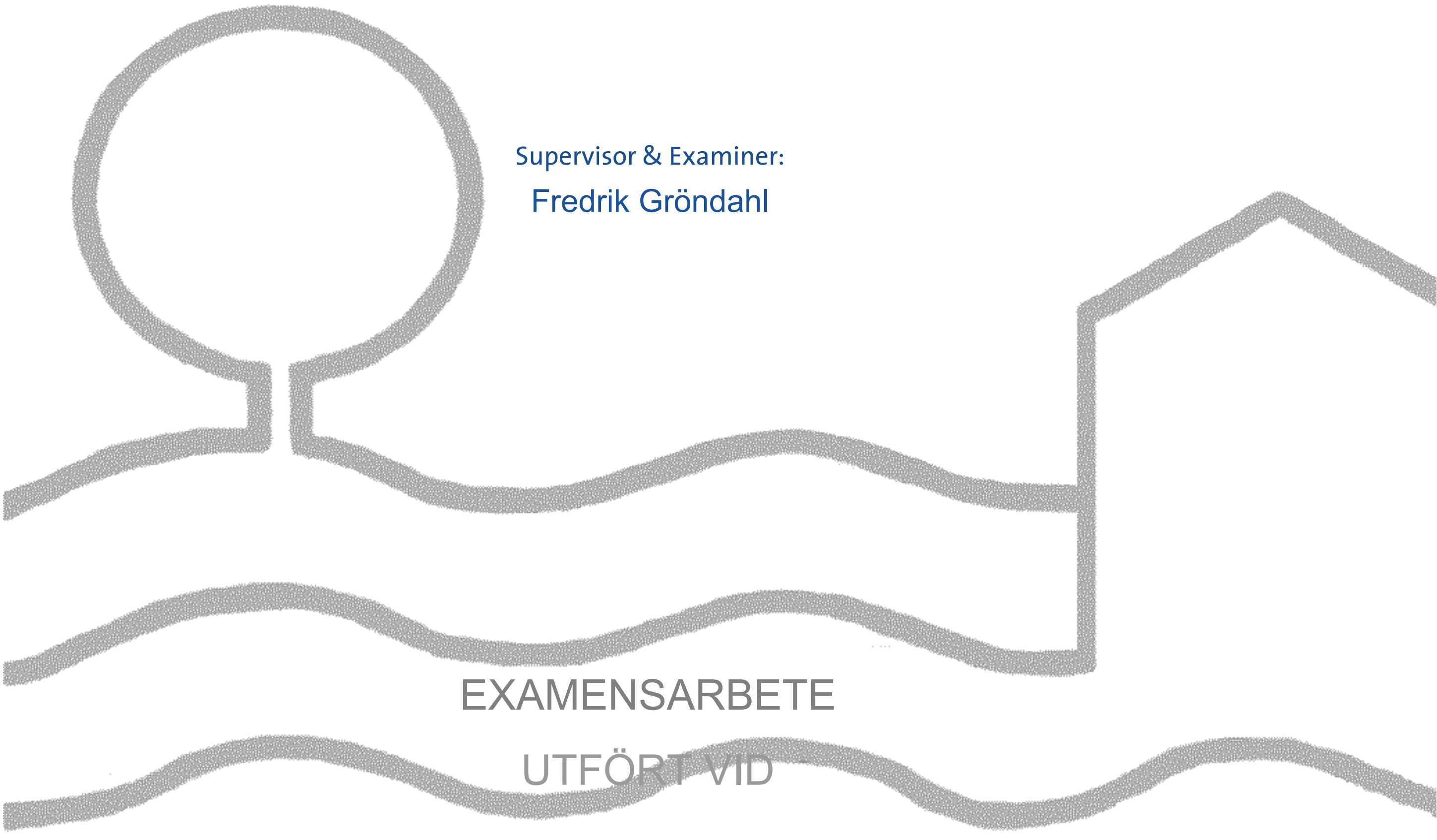

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Abstract

Eutrophication is one of the most serious environmental problems in the Baltic Sea due to factors such as nutrient discharges from different sources and long residence time. Eutrophication gives rise to increased primary production, often followed by oxygen depletion and disruption of important ecosystems. An action plan has been created by the Helsinki Commission (HELCOM) in order to achieve good ecological status of the Baltic Sea in the year of 2021. According to the action plan, 21 000 tonnes of nitrogen and 290 tonnes of phosphorus shall be decreased of the annual discharge from Sweden.

The aim of methods within ecological engineering is to solve environmental problems, and the applications ranging from the harvesting of existing ecosystems to the construction of new ecosystems. This study evaluates if harvest of algae, reed, and mussels can help meeting the goals of the action plan considerably, in accordance with areas and biomass amounts that need to be harvested, and to assess the efficiency of the three biomasses with regards to nutrient reduction. The potential of harvested biomasses as substrates in biogas production and as fertilizers is investigated, and how much fossil CO_2 that can be saved from being released to the atmosphere if net energy benefits, calculated from energy budgets in the biogas process, replaces fossil fuels.

Life cycle inventories which extend from the harvest (i.e. from the Baltic coast of Sweden) to the production of biogas have been made in order to investigate the biogas potential of algal, reed, and mussel biomass. Suitability of the three biomasses as fertilizers has been assessed through comparison between nutrient sufficiency of crops and nutrient contents of the three biomasses (i.e. based on quotients of nitrogen).

The quantity of biomass in the areas that can be harvested can help meeting the goals of the action plan drawn up by HELCOM, and mussels show to be most efficient with regards to nutrient reduction efficiency. Reed has the highest net energy benefit followed by algae, and both biomasses show potential of further investigation as substrates in the biogas production process. Mussels have low net energy benefit and thus are not a suitable substrate in biogas production. The three biomasses are suitable as fertilizers with respect to contents of nitrogen but the content of phosphorus occurs under the sufficiency levels for the crops (i.e. peas, grain, and sugar beets). For algae and reed, the potassium contents occur above the sufficiency level for peas and grain but under the level for sugar beets, mussels contain lower levels of potassium than the need of the investigated crops.

Keywords: eutrophication, ecological engineering, biogas, LCI, Baltic Sea, reed, mussels, algae, fertilizer, CO_2

Sammanfattning

Eutrofiering är ett av de största miljöhoten i Östersjön och orsakas av faktorer som utsläpp av näringsämnen från olika källor samt lång uppehållstid. Eutrofiering ger upphov till ökad primärproduktion där syrebrist och störning av viktiga ekosystem är vanliga påföljder. En aktionsplan har utformats av HELCOM som fastställer att Sverige ska reducera 21 000 ton kväve och 290 ton fosfor av de årliga utsläppen till Östersjön, med syftet att uppnå god ekologisk status år 2021. Metoder inom ecological engineering innefattar sund skörd av existerande ekosystem med syftet att lösa miljöproblem.

I den här studien undersöks om skörd av alger, vass och musslor kan hjälpa till att möta miljömålen med påtaglig effekt, samt mängder och ytor som måste skördas av de tre biomassorna. Effektiviteten med avseende på näringsreducering hos de tre biomassorna jämförs. Potentialen för användning av de skördade biomassorna som substrat i biogasproduktion samt som gödningsmedel undersöks, samt hur mycket CO_2 som kan besparas att släppas ut till atmosfären om nettoenergi från energibudgetar i biogasprocessen ersätter fossila bränslen. Energibudgetar som sträcker sig från skörd till biogasproduktion har utformats samt näringsinnehåll av de tre biomassorna jämfördes med näringsbehov hos vissa grödor för att ta reda på biomassornas eventuella potential som gödningsmedel.

Beträffande biomassor och areor som finns att skörda visade det sig att metoderna kan möta miljömålen utformade av HELCOM. Musslor visade sig vara den mest effektiva biomassan att skörda med avseende på näringsämnesreducering. Vass erhöll högst nettoenergiutbyte (i.e. baserat på energibudgetarna) följt av alger, därmed finns potential för vidare undersökning av de båda biomassorna som substrat i biogasprocesser. Nettoenergiutbytet i biogasprocessen hos musslor var lågt vilket visar att musslorna inte är lämpligt som substrat. De tre biomassorna uppvisar lämplighet som gödningsmedel med avseende på kväveinnehåll men innehållet av fosfor ligger under näringsbehovet hos de grödor som undersöktes. Alger och vass uppfyller kaliumbehovet hos ärter och spannmål, men inte hos sockerbetor. Musslornas kaliuminnehåll är lägre än näringsbehovet hos samtliga grödor.

Nyckelord: eutrofiering, ecological engineering, biogas, LCI, Östersjön, vass, blåmusslor, alger, gödningsmedel, CO_2

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Abbreviations

LCI	Life Cycle Inventory
ww	wet weight
dw	dry weight
vs	volatile solids
HELCOM	The Helsinki Commission

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1 Introduction

Eutrophication, the phenomenon when primary production is increased in an aquatic ecosystem due to increased input of nutrients (Lundberg, 2005), is one of the most serious environmental problems in the Baltic Sea (Gröndahl, 2008). The Baltic proper reaches from the Danish straits in the south to Åland sea in the north (SMF, 2005) with an area of $211*10^3$ km^3 and a volume of $13 * 10^3$ (Artioli *et al*, 2008)(see Figure 1.1). The eutrophication occurs due to long residence time of the Baltic Sea (i.e. 54 months) and high land based nutrient discharges. Nutrients are discharged to the Baltic Proper through different sources such as terrestrial sources, atmospheric deposition, release from sediment, and exchanges across marine boundaries (Artioli *et al*, 2008). Leakage of nutrients from agriculture is the main source that gives rise to algal blooms and eutrophication (Jordbruksverket, 2005).

Figure 1.1. The Baltic Sea where the thick black lines indicates the division into five sub-areas (Kautsky & Kautsky, 2000).

The increased primary production is often followed by oxygen depletion (Lindahl *et al*, 2005) as oxygen is consumed in the breakdown of organic matter that originate from heavy algal blooms (Gray, 2002) and growth of one-year filamentous algae, i.e. green, brown and red algae, eliminates seaweed (Malm & Engkvist, 2001). Filamentous algae grow on seaweed and thus prevent its photosynthesis and nutrient uptake, and also grow on the bottoms and thus prevent the fertilized eggs of the seaweed from attaching to the bottom (Malm & Engkvist, 2001). Biodiversity in coastal areas is important, and seaweed creates essential environments for other species (Brenner, 2007). The algae can be removed due to the shading and sweeping effects of well established seaweed, but in most cases the algae replaces seaweed and thus prevents its new recruitment. Large parts of the filamentous algae come loose and stratify at beaches and at ground shores in enormous amounts during the late part of summer, a problem that especially occurs in the south of Sweden (see Figure 1.2). The consequences are decreased coastal extensions and degradation of the most productive ecosystems of the sea. This gives rise to long term negative effects on the important ecosystems and to negative economical effects on tourism and fishing industry (Malm & Engkvist, 2001).

Figure 1.2. Enormous amounts of red algae on a shore in the south of Sweden (Malm & Engkvist, 2001).

An action plan has been drawn up by HELCOM which states that Sweden should reduce 21 000 tonnes of nitrogen and 290 tonnes of phosphorus of annual discharge, with the purpose to reach healthy ecological status in the year of 2021 (Miljödepartementet, 2008). In order to balance the surplus of nutrients from the Baltic Proper and to considerably meet the environmental goal of the action plan, satisfying measures need to be undertaken.

By applying methods within ecological engineering (i.e. harvest of naturally occurring biomasses such as algae, reed, and mussels) nutrients can be reduced from the sea and alternative products from harvested biomass, such as biogas and fertilizer, can be generated. Potential amounts that can be harvested from the Baltic coastline of Sweden determine, among other things, the extent of nutrient reduction and product extraction from the biomasses. In order to investigate if the methods could help meeting the goals according to the action plan, data for occurrence of the biomasses (i.e. of algae, reed and mussels) and corresponding nutrient concentrations have been collected.

LCI, which extends from the harvest (i.e. from the Baltic coast of Sweden) to the production of biogas has been made in order to investigate the biogas potential of the three biomasses. Net energy benefits have been calculated from energy balances where the energy demands, which include harvest, transport from harvest location to biogas plant, heating- and electricity demands in the biogas production process have been subtracted from the energy benefits. The biomass (i.e. of algae, reed, and mussels respectively) in the energy balances corresponds to one tonne of nitrogen.

In order to examine the suitability as fertilizers, nutrient contents of the three biomasses have been compared to nutrient sufficiency of nitrogen, phosphorus and potassium of crops. A limiting factor when used as fertilizer is the biomass content of heavy metals, i.e. cadmium. Limiting values of amount of cadmium as grams per hectare per year have been stated by KRAV and whether biomasses of algae, reed, and mussels exceed the limiting values need to be further investigated.

The alternative products give rise to positive environmental effects and indirect energy benefits i.e. net discharges of fossil CO_2 to the atmosphere is reduced when fossil fuels are replaced to biogas and energy is saved when harvested biomass replaces artificial fertilizer.

Harvesting techniques studied in this work are Aquatic plant harvester RS 2000 for the harvesting of algae and reeds, a floating device suitable for harvesting of water plants. Harvesting of long line mussel farms have been studied for mussels, which is a technology developed in Sweden

1.1 Initiatives of Ecological engineering

The aim of methods within ecological engineering is to solve environmental problems using methods ranging from the harvesting of existing ecosystems to the construction of new ecosystem (Mitch & Jorgensen, 1989). Initiatives of Ecological engineering methods are being undertaken by the municipality of Trelleborg and future initiatives are being planned as well; nutrients will be removed from the southern coast of Sweden through harvest of macro algae and Cyanobacteria. The harvested biomass will be used in biogas production and digester sludge of macro algae have potential to be used as fertilizer after removal of heavy metals. Growth and harvest of reed in new wetlands and large scale biogas production will be established (Gröndahl & Müller, 2008). Until now small scale mussel farming have taken place in the Baltic Sea, but within a near future, a project of greater scale will occur where test farms of mussels will be performed in three areas of the Baltic Sea; Trosa skärgård, Kalmarsund, and Puck Bay at Gdansbukten in Poland. The project is financed by Stiftelsen Baltic Sea 2020 and its main goal is to improve the water quality (Sveriges radio, 2009).

Earlier initiatives with the aim of removing nutrients through harvest of reed from Kållandsundet in Sweden have been performed by the municipality of Lidköping (Fredriksson, 2002). Finland and Estonia have done similar approaches in the Baltic Sea (Natura 2000 Networking programme, 2007). Nutrient removal through harvest of macro algae restrains negative effects of eutrophication (EU-life algae, 2001). A pilot studie of Gröndahl (2008) showed that harvest of the nitrogen fixing *Nodularia spumigena*, which provide the Baltic Sea with a relatively great amount of nitrogen, may restrain the effects of eutrophication in the Baltic Sea. A test farm of mussels at Askö marine research center in the Stockholm archipelago, with good outcome regarding the conditions of the Baltic Sea, has been provided by Nils Kautsky (Wessman, 2007). Mussel farming as a way of improving the water quality has been performed along the Swedish west coast for a long time (Sveriges radio, 2009). Nitrogen removal through mussel farms from the Gullmar fjord of the Swedish west coast have been shown by Lindahl *et al* (2005) to mitigate problems of eutrophication and that product such as agricultural fertilizer, seafood and fodder may be produced.

Detox AB, a company that within the environmental area offers technical consulting services, was commissioned by the municipality of Trelleborg to investigate the possibility of producing biogas from collected algae (Lindstedt, 2009). The collected algae had a significant content of organic material, but the content of inorganic material, mainly sand, showed to be significant (Davidsson, 2007). Result from Ascue & Nordberg (1998) shows that pretreatment of green algae in the biogas process, in order to increase the availability of the substrate to the microorganisms is essential (Melin, 2001). Even higher biogas potential compared to the theoretical value of algae has been shown by Hansson (1983), which can be a result of beneficial graft of microorganisms in the biogas process (Melin, 2001). According to Baran *et al* (2002), favorable results have been received from laboratory experiments with biogas production from reed (Eno, 2001). Most biogas plants apply processes where substrates of low dry matter content is used and problems might appear with substrates of high dry matter content, such as reed. Thus dry anaerobic digestion might be an alternative. However one draw back with this method is lack of experience, which makes it difficult to conclude whether it would be an effective measure or not (Eno, 2001). Lim *et al* (2008) have shown that anaerobic digestion of blue mussels can be ecologically, economically and socially feasible.

1.2 Aim

According to the action plan drawn up by HELCOM Sweden shall decrease 21 000 tonnes of nitrogen and 290 tonnes of phosphorus of its annual discharge in order to achieve good ecological status in the year of 2021. The aim of this work is to evaluate if methods within ecological engineering (i.e. harvest of algae, reed, and mussels) can help meeting the goals of the action plan considerably, in accordance with biomass amounts and areas that need to be harvested, and to compare the effectiveness of three biomasses with respect to nutrient reduction. To provide energy budgets that reach from harvest to biogas production, to calculate energy balances for the three biomasses, to compare the net energy benefits in order to investigate if biogas potential occurs and to examine the suitability as fertilizer with respect to nutrient contents in comparison to nutrient sufficiency of crops.

1.3 Biomasses in the Baltic proper

1.3.1 Algae

Heavy algal blooms in the Baltic Proper occur due to the surplus of nutrients and the internal distribution of nitrogen and phosphorus (SMHI, 2007), i.e. exchanges with sediments and across marine boundaries (Artioli *et al,* 2008). The potential amount of algae that can be harvested from the Baltic South coast of Sweden i.e. from Malmö to Simrishamn amounts to approximately 43 068 tonnes of dry weight per year (Davidsson & Ulfsdotter Turesson, 2008). The calculations of the potential amount of algae are estimated by Detox AB. The collection of algal biomass is assumed to take place in the water, and include the area from the coastline and 100 meters out in the water. The assumption of the quantities of algal biomass per hectare is based on the present collection performed by the municipality of Trelleborg (Barwén, 2009). The algal dry weight content of nitrogen, phosphorus, and potassium, is approximately 3.0 %, 0.2 %, and 1.3 % respectively (Davidsson & Ulfsdotter Turesson, 2008).

1.3.2 Reed

Reed is a freshwater species that show tolerance to different growth conditions (Soetaert *et al*, 2004), and tolerates salinity of 15-20 PSU. It can grow during >20 PSU if its deep roots can reach water with lower salinity (Soetaert *et al*, 2004). In Baltic proper vertical and horizontal salinity gradients are formed from a mix of marine water from the North Sea and land based fresh drainage water (Artioli *et al*, 2008). The salinity level decreases towards northeast (Lindqvist, 2008), and is about 6-8 PSU in the Baltic Proper and increases further south, to about 15-20 PSU in the southern Kattegat (Kautsky & Kautsky, 2000).

Reed is mainly thought to uptake nutrients from the soils, but can thrive on a range of substrates. When exposed to eutrophied water, reed extracts nutrients on the lower part of the culm through finely branched roots (Granéli, 1984). Rhizomes are the perennial underground biomass of reed that store nutrients and photosynthetic products. Annual stems are developed out of the rhizomes (Hansen *et al*, 2007). Due to the storage within the rhizomes, reed is able to grow fast in late spring, with no dependence of photosynthesis (Granéli, 1984). The rhizomes also play a role in vegetative spreading of reed (Hansen *et al,* 2007). The panicles constitute of hundreds of spikelets and each spikelet have got around six hermaphrodite florets (Ishii & Kadono, 2002). In early autumn shoots are formed out of the rhizomes, which stay dormant until the next spring (Granéli, 1984) (see Figure 1.3).

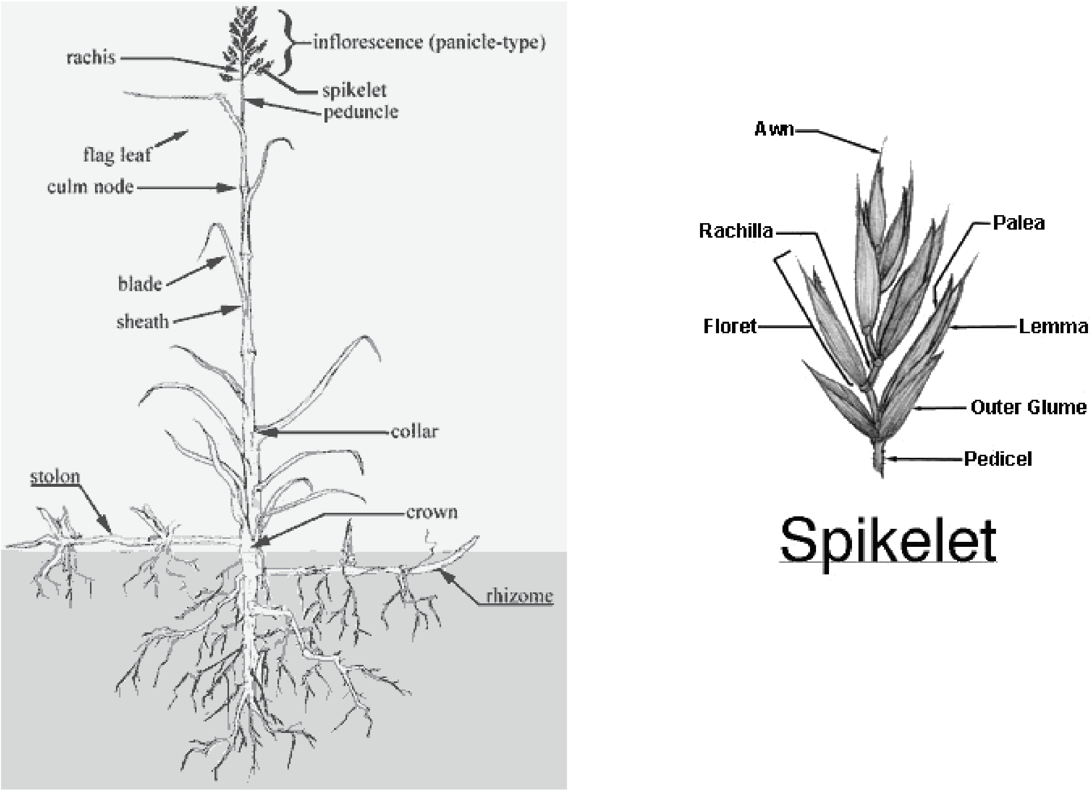

Figure 1.3. Grass structure of *Phragmites australis* (From Hannaway, 2000).

Reed grows along the Baltic coast in large monospecific stands, on a wide variety of substrates (Granéli, 1984). There are no documentations of the specific amount of reed biomass growing along the Baltic coast of Sweden (Granéli, 2008) but the total reed area of Sweden amounts to 100 000 hectares (Hansson & Fredriksson, 2004). The biomass above ground amounts to 1 kg dw m^{-2} (Granéli, 1984) according to investigation of reed stands in the middle and in the south of Sweden performed in August (Fredriksson, 2002). The nutrient content per kg dry weight is 0.94 g nitrogen, 0.9 g phosphorus and 6.6 g potassium (Fredriksson, 2002).

1.3.3 Mussels

Blue mussels (i.e. *Mytilus edulis*) grow on hard substrates down to depths over 30 m and prefer salinity above 18 S. As a result of the low salinity in the brackish environment of the Baltic Proper (as depicted above), the growth rate and size is reduced compared to the North Sea (Kautsky & Kautsky, 2000) to around 3 cm (Fiskeriverket, 2007). Mussels clean water by filter feeding (Rice, 2001) through their gills (Griffin *et al*, 2006) and feed on phytoplankton (Ribeiro Guevara *et al*, 2005), which they sort with respect to nutritional value (see Figure 1.4). The filtration rate is around 1- 4 liters per hour (Rice, 2001).

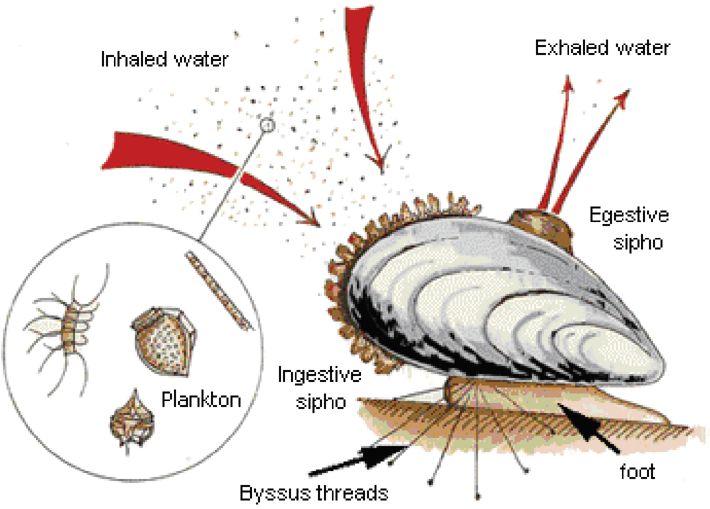

Figure 1.4. Nutrition and respiration of a blue mussel (From Aquascope, 2000).

Faeces and pseudofaeces of mussels are aggregated through coating with mucus (Zhou *et al*, 2006) which makes the material more resistant to re-suspension (Griffin *et al*, 2006) and make them sink at velocities around 40 times compared to other particles (uncoated with lower densities) (Zhou *et al*, 2006). Thus the turbidity decreases, the benthic productivity increases (Griffin *et al*, 2006) and a top-down control of phytoplankton biomass is created (Zhou *et al*, 2006). Although the physiological conditions are not ideal, *M. edulis* is dominating the Baltic Sea and 90% of the animal biomass growing on hard bottoms constitutes of *M.edulis* (Kautsky & Kautsky, 2000). The nutrient content of mussels amounts to approximately 1.1 % nitrogen and 0.07 % phosphorus (Haamer *et al*, 1999) and the potassium content to 0.12 % (Olrog & Christensson, 2003).

1.4 Harvest techniques

1.4.1 Aquatic Plant Harvester RS 2000

Aquatic Plant Harvester RS 2000 is a floating device (see Figure 1.5) constructed with front conveyors which makes harvest of water plants, such as algae and reed possible. It has got two steplessly adjustable paddle wheels with their own hydraulic circuits and three cutters of which two are vertical and one is horizontal (RS-Planering AB, 2008). The rate of harvest varies and depends among other things on locations of unloading spots for the harvest machine. Normally the harvesting rate of collecting algae is faster than the rate of collecting reed, because unlike reed, algae do not cover the water surface to the same extent. Generally, algae can be harvested at an approximate rate of 0.7 hectares per hour and reed at a rate of 0.4 hectares per hour for straw lengths of 2.5 meters (about 0.7 hectares per hour for straws of 1 meters) (Salin, 2009).

Figure 1.5. Aquatic Plant Harvester RS 2000 (From RS-Planering AB, 2008).

1.4.2 Long line mussel farm

The long line mussel farm is a method of farming mussels (see Figure 1.6). Rope wires are held up by floating barrels, and from the rope wires, mussel lines are hanged (Sanchez *et al,* 2004). Every unit consists of approximately 9 lines and the long line farm functions as a three-dimensional bio filter (Griffin *et al*, 2006) with an area of approximately 0.5 ha (Lindqvist, 2008, see Figure 1.2.2). Mussel farms demand water depths of 6-25 m at sheltered areas (Lindahl *et al*, 2005), the Stockholm archipelago has a water area of 372 500 hectares (Nordiska Ministerrådet, 2009). While the settling of the mussels occurs, mussel rigs are rigged up. Settling is the phenomenon when freely swimming mussel larvae settle down, and the larvae settle on the mussel rigs from where they feed on foodstuffs that naturally exists in the surrounding water. The time for settling varies depending on water temperature but generally starts in mid June and continues the summer through (Sanchez *et al*, 2004). After about 2.5 years about 75 tonnes wet weight per mussel farm can be harvested (Lindqvist, 2008). The mussels are harvested through scraping the mussels off the lines by a machine (Sanchez *et al*, 2004).

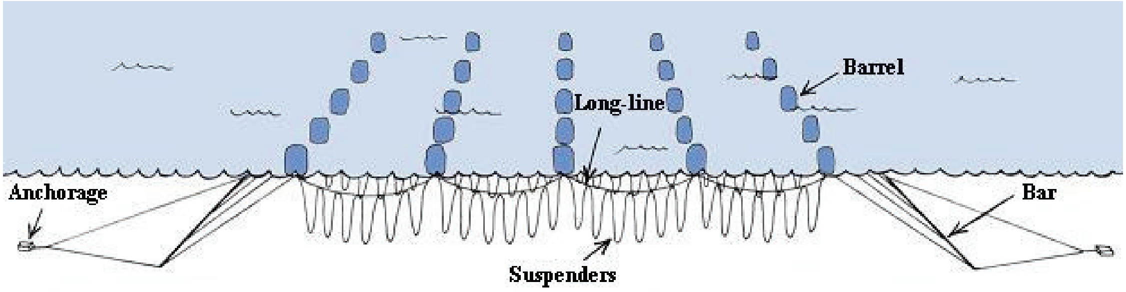

Figure 1.6. Description of a long line mussel farm (From Norell, 2005).

1.5 Biogas production

1.5.1 Volatile solids

The volatile solids (vs) constitute the organic matter content of a substrate (Persson, 2006). Biogas is formed when volatile solids are broken down anaerobically (Berglund & Börjesson, 2003) by methane forming microorganisms (Nilsson, 2000). Biogas mainly consists of methane (50-60 volume-%) and carbondioxide (25-40 volume-%) (Nilsson, 2000) and can also contain hydrogen gas, sulphur-hydrogen, and steam (Berglund & Börjesson, 2003). Different factors have influence on the biogas production, such as temperature and technique of the biogas production process, pre-treatment of the substrate and chemical composition of the substrate (Berglund & Börjesson, 2003).

Biogas is formed during anaerobic conditions, thus molecules with small amounts of oxygen, such as fat, generates higher amount of methane compared to other molecules (Berglund & Börjesson, 2003), such as proteins followed by carbohydrates (Nilsson, 2000). The nitrogen content of proteins is higher compared to the other molecules mentioned (i.e. carbohydrates and fat). In the degradation process, the organically bound nitrogen is transformed to ammonia, which has an inhibitive effect on the microorganisms (Nilsson, 2000). The methane potential of algae, reed, mussels, and sludge, amounts to 200 l CH_4/kg volatile solids, 180 l CH_4/kg volatile solids, 8 l CH_4/0.5 kg wet weight, and 0.625 m^3 CH_4/kg volatile solids respectively (Davidsson, 2007, Fredriksson, 2002, Lim *et al*, 2008, and Lantz, 2007 respectively).

1.5.2 Microbiology

Biogas is formed through anaerobic degradation of organic matter by specialized microorganisms (Berglund, 2006), the formation occurs in four steps. In the hydrolysis step, extracellular enzymes transform complex polymers of the organic matter to monomers, i.e. fat is hydrolyzed into fatty acids, proteins into amino acids and cellulose into simple sugars. In the acid formation step, fermentative bacteria degrade the monomers (i.e. from the hydrolysis step) to shorter fatty acids, alcohols, hydrogen gas, and carbon dioxide. In the acetic acid formation step, the degraded monomers from the previous step are transformed to acetic acid, hydrogen gas, and carbon dioxide. The methane formation step is performed by sensitive bacteria that develop methane from acetic acid or carbon dioxide and hydrogen i.e. created in the acetic acid formation step. High concentration of ammonia, phosphorus, potassium, heavy metals, sulphur, and certain fatty acids can restrain the sensitive methane forming bacteria (Nilsson, 2000).

2 Methods

Eutrophication is one of the most serious environmental problems in the Baltic Sea due to factors such as long residence time and nutrient discharges from different sources, especially agricultural. Eutrophication gives rise to increased primary production, often followed by oxygen depletion and disruption of important ecosystems and decreased coastal extensions, which has negative economical effects on tourism and fishing industry.

In order to achieve good ecological status of the Balitc Sea in the year of 2021, an action plan has been created by the Helsinki Commission (HELCOM). The action plan states that Sweden should reduce 21 000 tonnes of nitrogen and 290 tonnes of phosphorus of its annual discharge to the Baltic Sea (see Table 2.1). This thesis is a first step in a tenability and potential study in order to determine if ecological engineering through the harvesting of algae, reed, and mussels along the Swedish Baltic coast considerably can help to meet these environmental goals.

In order to capture the biogas potential of the biomass of algae, reeds and mussels, LCI that stretches between harvesting and biogas production has been created. The energy demands in the LCI represent harvest, transportation from harvest spot to a central biogas plant and electricity- and heating demands and the energy benefits represent the potential of methane extraction of the three biomasses in the life cycle inventories.

Indirect energy benefits arise when artificial fertilizer is replaced by biomass of algae, reed, and mussels. Energy demands for production of artificial fertilizer per kg nitrogen and per kg phosphorus are used in order to determine indirect energy benefits when biomass corresponding to one tonne of nitrogen replaces artificial fertilizers. Nutrient contents of the three biomasses are compared to nutrient sufficiency of nitrogen, phosphorus, and potassium of crops in order to examine the suitability as fertilizers. The amount of fossil CO_2 that can be saved from being released into the atmosphere is calculated with the purpose to find positive environmental effects as a result of the replacement of fossil fuels to biogas.

2.1 Biomass contents of nutrients

Biomass contents of nutrients, dry weight and volatile solids have been collected from the literature and the data of the three biomasses is together with corresponding references presented in Table 1.1. In order to receive the same unit for each biomass, the contents have been converted into a proportion of wet weight (i.e. nutrients, dry weight and volatile solids) as shown in Equation 1. In Equation 2, wet weight volatile solid contents of algae, reed, mussels, and sludge were calculated.

Wet weight nutrient proportions (i.e. nitrogen and phosphorus) of algae, reed, and mussels respectively, Nw_{ij}, was calculated as

$$Nw_{ij} = Nd_{ij} * \gamma_i \qquad (1)$$

Where Nd_{ij} is dry weight nutrient content (i.e. nitrogen and phosphorus) of algae, reed, and mussels respectively, and γ_i is wet weight dry weight proportion of algae, reed, and mussels respectively (i.e. i represents algae, reed, and mussels respectively and j represent nitrogen and phosphorus, respectively).

Wet weight volatile solid proportion of algae, reed, mussels, and sludge respectively, ε_i, was calculated as

$$\varepsilon_i = \delta_i * \gamma_i \qquad (2)$$

Where δ_i = proportion volatile solids of dry weight and γ_i = proportion dry weight of wet weight, of algae, reed, mussels, and sludge (i.e. i represents algae, reed, mussels, and sludge respectively).

Table 1.1 Biomass contents of nutrients, dry weight, and volatile solids.

	Dry weight [kg dw kg^{-1} ww]	Nitrogen content [kg N kg^{-1} dw]	Phosphorus content [kg P kg^{-1} dw]	Volatile solids content [kg vs kg^{-1} dw]
Algae	0.13[a*]	0.025[e*]	0.0021 [e*]	0.65[h*]
Reed	0.35[b]	0.009[f]	0.0009 [f]	0.95[f]
Mussels	0.02[c]	0.53 [g, i]	0.034 [g, i]	0.86[c]
Sludge	0.045[d*]	n.a.	n.a.	0.68[d*]

[a]Fransson [11]; [b]Eno [9]; [c]Lim *et al* [24]; [d]Lantz [23]. [e]Davidsson and Ulfsdotter Turesson [7]; [f]Fredriksson [12]; [g]Haamer *et al* [17]; [h]Davidsson [6], [i]Recalculated from Lim *et al* [24]; n.a.- not addressed.
[*]Average of reported values.

2.2 Nutrient amounts and areas

2.2.1 Nutrient amounts

In order to estimate the potential amounts of nutrients that annually can be harvested from the Baltic Sea, data for occurrence of the biomasses (i.e. of algae, reed, and mussels) and corresponding nutrient concentrations were collected. With the purpose to investigate if the methods can help to meet the objectives of the action plan substantially (i.e that states that Sweden shall reduce 21 000 tonnes of nitrogen and 290 tonnes of phosphorus of its annual discharge), the data of potential amounts of nutrients were compared to the nutrient amounts of the action plan.

According to report from Davidsson & Ulfsdotter Turesson (2008) the potential amount of algal biomass that annually can be harvested from the Swedish south coast that reaches from Malmö to Simrishamn amounts to 43 068 tonnes of dry weight. The calculations of the potential amount are made by Detox AB. The collection is assumed to take place in the water, with an area that extends 100 meters into the water from the coastline. The assumption of the quantities of algal biomass per hectare is based on the present collection performed by the municipality of Trelleborg (Barwén, 2009). The corresponding wet weight (i.e. of 43 068 tonnes of dry weight) was calculated and from wet weight nutrient contents, the content of nitrogen and phosphorus of the corresponding biomass was calculated (see Equation 3). The nutrient amounts of the algal biomass were calculated as shares of the nutrient amounts of the action plan in order to investigate whether obvious influence occurred.

Contents of nitrogen and phosphorus, y,n_{algae} and y,p_{algae} [tonnes] of the potential biomass that annually can be harvested from the Swedish south coast, was calculated as

$$y_{i,algae} = w_{algae} * Nw_{algae} \qquad (3)$$

Where w_{algae} = the corresponding wet weight of potential dry weight of algae that annually can be harvested from the Swedish south coast and Nw_{algae} = share nutrients (i.e. N and P) of wet weight of algae.

Reed grows in shallow bays as large mono-specific stands in the Baltic Proper (Granéli, 1984) but the exact area is not documented (Granéli, 2008). Mussel farms demand sheltered areas at water depths of 6-25 meters (Lindahl *et al*, 2005). While there are no documentations of potential biomasses of reed and mussels that annually can be harvested from the Baltic coastline of Sweden, the potential amount of nitrogen harvested through algae (i.e. y,n_{algae}) was used as a comparative measure in this work. The biomasses of reed and mussels, in order to achieve the same amount of nitrogen and the amount of phosphorus in the corresponding biomass was calculated as shown in Equations 4-5. The amount of phosphorus in the corresponding biomass was calculated as a percentage of the amount of phosphorus in the action plan.

The amount of wet weight, of reed and mussels, $wn_{i,}$ that need to be harvested in order to achieve y,n_{algae} (i.e. the potential amount of nitrogen harvested through algae used as a comparative measure in this work) was calculated as

$$wn_i = (1 / \alpha_i) * y,n_{algae} \qquad (4)$$

Where α_i is wet weight nitrogen proportion of reed and mussels.

The amount of phosphorus in biomass of reed and mussels corresponding to 1100 tonnes of nitrogen respectively, y,p_i was calculated as

$$y,p_i = \beta_i * wn_i \qquad (5)$$

2.2.2 Areas

Data were searched for in order to determine the area of reed that need to be harvested and the water area that need to be covered with mussel farms in order to harvest the potential amount of nitrogen (i.e. used as a comparative measure in this work) annually from the Swedish Baltic coastline. In order to receive these results, data of the amount of reed per hectare and the area and the amount of biomass per mussel farm were collected from the literature (see Table 2.2). The areas were calculated as shown in Equations 6-8, and in order to evaluate the realism of the calculated areas in comparison to the Baltic coast of Sweden, corresponding areas were compared with Swedish total reed area and with the water area in the Stockholm archipelago. Swedish total reed area and the water area of the Stockholm archipelago were collected from reports of Hansson & Fredriksson (2004) and Nordiska ministerrådet (2009), respectively (see Table 2.2).

Nitrogen content per hectare, N_i of reed and mussels, respectively, where calculated as

$$N_i = B_i * \alpha_i \qquad (6)$$

Where B_i is wet weight per hectare of reed and mussels, respectively.

The area of reed that need to be harvested and the water area that need to be covered with mussel farms in order to annually harvest 1100 tonnes of nitrogen, A_i, was calculated as shown in Equation 6. While harvest of mussel farms occur every 2.5 years, the area that annually need to be harvested has been multiplied by 2.5 i.e. in order to receive the area that need to be covered with mussel farms in order to receive 1100 tonnes of nitrogen annually.

$$A_i = y,n_{algae} / N_i \qquad (7)$$

In order to appreciate results in Equation 7, A_{reed} and $A_{mussels}$ were calculated as proportions, S_i of Swedish total reed area and of the water area of the Stockholm archipelago as

$$S_i = A_i/T_i \tag{8}$$

Where S_i represents the proportions and T_{reed} = Swedish total reed area and $T_{mussels}$ = the water area of the Stockholm archipelago.

Table 2.2. Biomass of the reeds and mussels per area unit, Swedish total reed area, and the water area of the Stockholm archipelago.

Reed [kg dw m^{-2}]	Mussels [tonnes ww ha^{-1}]	Swedish total reed area [ha]	Water area of the Stockholm archipelago [ha]	Area of a mussel farm [ha]
1.0[a]	150[b]	100 000[c]	372 500[d]	0.5[b]

[a]Granéli, 1984; [b]Lindqvist, 2008; [c]Hansson & Fredriksson, 2004; [d]Nordiska ministerrådet, 2009

Life cycle inventory

Life cycle inventory that reaches from the harvest (i.e. of algae, reed, and mussels from the Swedish Baltic coast line) to the production of biogas has been created. The energy benefit represents the potential of methane extraction of the three biomasses and the energy consumed during the harvest, transportation from harvest site to a central biogas plant, and electricity- and heating needs representing the energy requirements of the life cycle inventory. Energy balances where energy demands are subtracted from energy benefit were calculated in order to examine the potential of energy extraction of the three biomasses.

2.3 System boundaries

The LCI embraces harvest including transportation back and forth between harvest spot and shore, transport from shore to biogas plant, heating and electricity demands in the biogas plant. No consideration is taken of any storing of the biomasses that may occur. While digestate may potentially be used for other products, e.g. liquid, agricultural fertilizer, energy demands from transportation and handling of digester sludge is not included within the system boundaries. Energy requirements from the upgrading of biogas (and other fuels) are also exempt (see Figure 1.5). The energy demand in the biogas production process i.e. heating and electricity is calculated as shares of the energy in the biogas produced, which in reality would be individual according to substrate used in the process. Positive environmental effects are based on the amounts of fossil CO_2 that can be saved from being released into the atmosphere i.e. if biogas from net energy benefits, calculated in the LCA, replaces a fossil fuel. No account has been taken to the CO_2 emissions from the life cycle of fuels (i.e. biogas and fossil fuels). The suitability of the biomasses as fertilizers is only based on the comparison between nutrient contents of the biomasses and nutrient sufficiency of some crops. No investigation concerning heavy metal contents (i.e. cadmium), toxins etc. has been done.

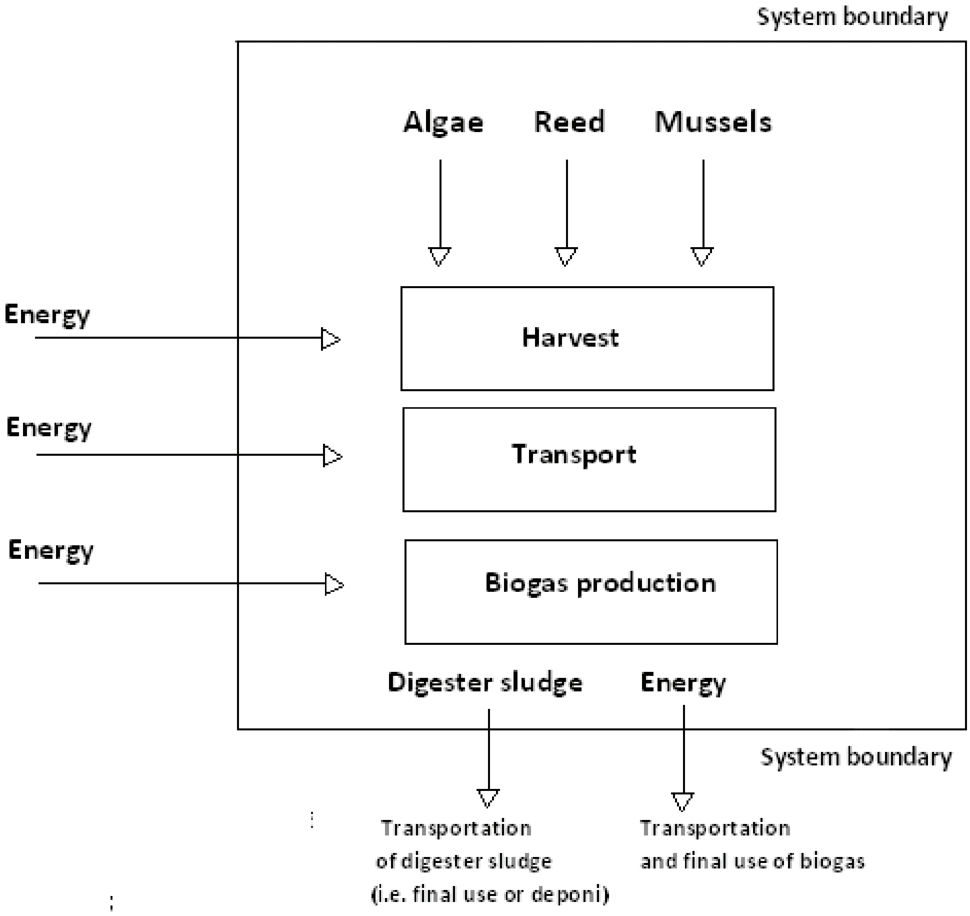

Figure 1.5. Energy scheme in the biogas production process that reaches from harvest to biogas production of biomasses of algae, reed, and mussels.

2.4 Energy benefit

Factors such as volatile solid content of biomass, and how well suited the organic matter of the volatile solids are as substrates for the microorganisms in the biogas production process have got influence on the energy potential. Data, in order to investigate the energy potential of algae, reed, and mussels and to appreciate the energy potential of the three biomasses in comparison to a reference, where searched for. Data of liter CH_4 that can be extracted from biomass per kg volatile solids of algae and reed, respectively, and per 0.5 kg wet weight of mussels, and volatile solid biogas potential of sludge has been collected from the literature (see Table 3.1).

Kg wet weight of mussels were transformed to kg volatile solids in Equation 9 in order to make mussels comparable to the other two biomasses, including sludge. The energy potential per tonne volatile solids of the substrates was calculated in Equation 10. In order to further analyze the energy potential of the three biomasses including sludge, energy potential per tonne dry weight and wet weight respectively, were calculated in Equations 11-12.

The energy potential in terms of liter CH4 per kg volatile solids of mussels, $\kappa_{mussels}$ was calculated as

$\kappa_{mussels} = \iota_{mussels} / (\gamma_{mussel} * \delta_{mussel})$ (9)

Where $\iota_{mussels}$ = energy potential as liter CH_4 per kg wet weight of mussels

The energy in units of MJ/tonne volatile solids, μ_{vs_i}, of algae, reed, mussels, and sludge was calculated as

$\mu_{vs\_i} = \kappa_i * \lambda * 1000$ (10)

Where κ_i = energy potential as liter CH_4 per kg volatile solids of algae, reed, mussels, and sludge respectively, and λ = MJ/l CH_4

MJ/tonne dry weight, μ_{dw_i}, and wet weight, μ_{ww_i}, of algae, reed, mussels, and sludge respectively, was calculated as

$\mu_{dw\_i} = \mu_{vs\_i} * \delta_i$ (11)

$\mu_{ww\_i} = \mu_{dw\_i} * \gamma_i$ (12)

To determine the energy potential for biomass of equivalent amounts of nitrogen, energy potential of biomass corresponding to one tonne of nitrogen was calculated as shown in Equation 13. In order to visualize the energy benefits of biomass corresponding to one tonne of nitrogen, number of Swedish average households that annually can be heated from the corresponding energy benefit was calculated as shown in Equation 14. In order to receive these results, data of energy demand from annual heating of an average Swedish household were collected from report of Davidsson & Ulfsdotter Turesson (2008) shown in Table 3.1.

The energy benefit from biomass corresponding to one tonne of nitrogen of algae, reed, and mussels respectively, μ_{N_i}, was calculated as

$$\mu_{N\_i} = \mu_{ww\_i} / \alpha_i \qquad (13)$$

The number of Swedish average households that annually can be heated from the energy benefit of biomass corresponding to one tonne of nitrogen, H_b, was calculated as

$$H_b = \mu_{N\_i} / H_d \qquad (14)$$

Where H_d is heating demand of an average Swedish household (transformed to MJ from kWh).

Table 3.1. Methane yield of algae, reed, mussels, and sludge.

Algae [l CH_4 kg^{-1} vs]	Reed [l CH_4 kg^{-1} vs]	Mussels [l CH_4 kg^{-1} 0.5 ww]	Sludge [m^3 kg^{-1} vs]
200[a]	180[b]	8[c]	0.625[d*]

[a]Davidsson, 2007; [b]Fredriksson, 2002; [c]Lim et al, 2008; Lantz, 2007; [*]average of reported values

2.5 Energy demand from harvest

The harvest technique for algae and reed studied in this life cycle analysis is a prototype called Aquatic plant harvester RS 2000 and the technique studied for mussels is harvest of long-line mussel farms. To determine the energy demand of Aquatic plant harvester RS 2000, data of harvest capacity and energy consumption were collected. Hectares harvested per hour of algae and reed, tonnes of wet weight harvested per hour of algae and working hours per day were received from Salin (2008) and tonnes of reed dry weight harvested per hectare from report of Fredriksson (2002) (see Table 4.1a). Calculations with respect to the harvesting capacity of RS 2000 (i.e. for algae and reed) are shown in Equations 15-18.

Hectares harvested per day of algae and reed, ν_{day_i} were calculated as

$$\nu_{day\_i} = h_{day} * \nu_i \qquad (15)$$

Where h_{day} = hours per working day and ν_{algae} = hectares harvested per hour of algae and reed respectively.

Tonnes wet weight harvested per day of algae, ξ_{day_algae}, and reed, ξ_{day_reed}, were calculated in Equations 16-17.

$$\xi_{day\_algae} = \xi_{algae} * h_{day} \qquad (16)$$

Where ξ_{algae} = tonnes of wet weight harvested per hour of algae

$$\xi_{day\_reed} = \nu_{day\_reed} * \xi_{dw\_reed} / \gamma_{reed} \qquad (17)$$

Where ν_{day_reed} = hectares harvested per day of reed, and ξ_{dw_reed} = tonnes of dry weight per hectare of reed.

Tonnes of nitrogen harvested per day of algae and reed respectively, ξ_{N_i} was calculated as

$$\xi_{N\_i} = \xi_{day\_i} * \alpha_i \qquad (18)$$

Table 4.1a. Harvest velocity of Aquatic Plant harvester RS 2000 and occurrence of reed.

Algae [ha hr^{-1}]	Algae [tonne ww hr^{-1}]	Reed [ha hr^{-1}]	Reed [g dw m^{-2}]
0.7[a]	9[a]	0.4[a]	1002[b]

[a]Salin, 2008; [b]Fredriksson, 2002

Table 4.1b. Working hours per day and energy demand per day of Aquatic Plant harvester RS 2000.

Working day [hrs]	Energy demand RS 2000 [l diesel working day^{-1}]	Energy content of diesel [MJ l^{-1}diesel]
8[a]	50[a*]	41.5 [b]

[a]Salin, 2008; [b]Börjesson, 2006
[*]Including harvest, idling, and transportation between harvest location and shore.

2.5.1 Energy demand from harvest of algae and reed with Aquatic Plant Harvester RS 2000

Energy demand per day (as liter diesel per 8 hours working day), which includes idling, harvesting and transportation to the shore, was received from Salin (2008) and energy content (as MJ per liter diesel) were received from the report of Börjesson (2006)(see Table 4.1b). Calculations of energy demand from harvest of algal- and reed biomass of one tonne wet weight and of biomass equal to one tonne of nitrogen are shown in Equations 19-21.

Energy demand per working day [MJ] with RS 2000, E_{rs2000}, was transformed from liter diesel/day as

$$E_{rs2000} = [\text{l diesel/day}]*[\text{MJ/l diesel}] = [\text{MJ/day}] \qquad (19)$$

Energy demand per tonne wet weight of algae and reed respectively, E_{ww_i} harvested was calculated as

$$E_{ww\_i} = E_{rs2000} / \xi_{day\_i} \qquad (20)$$

Energy demand of biomass corresponding to one tonne nitrogen of reed and algae respectively, E_{N_i} was calculated as

$$E_{N\_i} = E_{rs2000} / \xi_{N\_i} \qquad (21)$$

2.5.2 Energy demand from harvest of mussels per long-line mussel farm

Data of energy demand, which includes harvest of mussel bands and transportation to harvest location (i.e. there and back), per long-line mussel farm were received from Lindqvist (2008) and Granhed (2009)(see Table 4.2). Calculations of energy demand from harvest of mussel biomass equal to one tonne wet weight and of mussel biomass equal to one tonne of nitrogen are shown in Equations 22-24.

Energy demand from harvest of a long-line mussel farm including transport, $E_{l\text{-}l}$, was transformed from liter diesel/day as

$$E_{l\text{-}l} = [\text{l diesel/mussel farm}]*[\text{MJ/l diesel}] = [\text{MJ/mussel farm}] \qquad (22)$$

Energy demand per tonne mussel wet weight, $E_{ww\_mussels}$, was calculated as

$$E_{ww\_mussels} = E_{l\text{-}l} / \xi l\text{-}l \qquad (23)$$

Where $\xi l\text{-}l$ = tonnes of mussel wet weight per long-line mussel farm.

Energy demand to harvest mussel biomass corresponding to one of tonne nitrogen, $E_{N\_mussels}$, was calculated as

$$E_{N\_mussels} = E_{l\text{-}l} / (\xi l\text{-}l * \alpha_{mussel}) \qquad (24)$$

Table 4.2. Biomass per mussel farm and energy demands including harvest of mussel farm and transport.

Biomass per mussel farm [tonnes]	Harvest time per mussel farm [hrs]	Energy demand of harvest [l diesel hr^{-1}]	Transport time [hrs]	Energy demand of transport [l diesel hr^{-1}]
75[a]	30[b]	15[b]	2[b]	50[b]

[a] Lindqvist, 2008

[b] Granhed, 2009.

2.6 Energy demand from transport

The energy demand from transport between the harvest location and a central biogas plant is included in this work. In order to determine the energy demand from transport of biomass per tonne wet weight and equal to one tonne nitrogen a distance of 10 km and 100 km respectively, data from report of Berglund and Börjesson (2003) was used. The energy demand from the report (e.g. Berglund and Börjesson (2003)) 8 MJ was based on transport per tonne of dry weight including 30% dw per kilometer with 4-tonne-trucks.

Dry weight of 30 % was transformed to its corresponding wet weight and the energy demand from transporting biomass per tonne wet weight per 10 km and 100 km respectively, was calculated by Equation 25. Energy demand from transportation biomass of algae, reed, and mussels, equal to one tonne of nitrogen per 10 km and 100 km respectively, was calculated in Equation 26. The transport distance varies depending on locations of the harvest area and of the biogas plant used in the process. Due to this fact, energy demands due to different transport distances are presented in Chapter 7.

The energy demand from transporting biomass per tonne wet weight a distance of 10 km and 100 km respectively, ς_i was calculated as

$$\varsigma\_i = \varsigma * i / \rho_{ww} \qquad (25)$$

Where ς is energy demand per tonne of dry weight per km, i represents 10 km and 100 km and ρ_{ww} represents wet weight of transported biomass.

The energy demand from transportation of biomass equal to one tonne of nitrogen of algae, reed and mussels respectively, 10 km and 100 km, ς_{N_ij}, was calculated as

$$\varsigma_{N\_ij} = (1 / \alpha_i)* \varsigma\_ij \qquad (26)$$

Where i represents transport distances of 10 km and 100 km and j represents algae, reed, and mussels respectively.

2.7 Heating- and electricity demand

Heating- and electricity demands occur in the biogas process from heating and hygienization and from stirring, pumping, and milling the substrate etc (Berglund & Börjesson, 2003). In this study heating- and electricity demands are estimated as percent of the energy content of the biogas produced (13 % and 11 % from heating and electricity respectively). These shares where collected from the report of Berglund & Börjesson (2003) and was based on mesophilic digestion. In reality, the composition of the substrate and the design of the biogas plant control the size of these demands (Berglund & Börjesson, 2003).

The demands are calculated for biogas production from biomass equal to one tonne of nitrogen, D_{eh_i}, of algae, reed, and mussels respectively, as

$$D_{eh\_i} = D_{eh} * \mu_{N\_i} \qquad (27)$$

Where D_{eh} is demand from heating and electricity in the biogas process and μ_{N_i} is energy benefit from biomass corresponding to one tonne of nitrogen of algae, reed, and mussels respectively.

2.8 Energy balance

In order to investigate the energy potential of the three biomasses, energy balances were calculated from the energy benefits and energy demands of the life cycle analyses. The energy demands from harvest, transport, heating, and electricity were subtracted from the energy benefit. Depending on the location of the harvest spot and of the nearest biogas plant, the transport distance varies. In order to visualize the influence of energy demand regarding transport distance, energy balances excluding energy demand from transport (i.e. including energy demand from harvest, heating and electricity) were calculated in Equation 28 for biomass corresponding to one tonne of nitrogen of algae, reed, and mussels respectively. In Equation 29 energy balances including transport distances of 10 km and 100 km, were calculated. In order to visualize the positive net energy benefit from Equation 29 (i.e. including demands from transport of 10 km and 100 km, respectively), the number of Swedish average households that annually can be heated were calculated in Equation 30.

The energy balance excluding energy demand from transport, E_b, was calculated as

$$E_b = \mu_{N\_i} - (E_{N\_i} + D_{eh\_i}) \qquad (28)$$

The energy balance including transport distance of 10 km and 100 km respectively, E_{b_i}, was calculated as

$$E_{b\_i} = E_b = \mu_{N\_i} - (E_{N\_i} + \varsigma_{N\_i\,j} + D_{eh\_i}) \qquad (29)$$

The number of Swedish households that can be heated from positive net energy benefits from energy balances including transport of 10 km and 100 km respectively, H_{b_ij}, was calculated as

$$H_{b\_ij} = E_{b\_ij} / H_d \qquad (30)$$

Where i represents transport distances of 10 km and 100 km respectively and j represents algae, reed, and mussels respectively.

2.9 Distance that the biomasses can be transported before the net energy benefit is consumed

The distance that biomass can be transported before the positive net energy benefit is consumed, D_{net} was calculated as

$$D_{net} = E_b / \varsigma_{N\_1km} \qquad (31)$$

Where ς_{N_1km} = energy demand from transportation of biomass per km
(net energy benefit per tonne wet weight is shown in Figures 6.1-6.2)

2.10 Indirect energy benefits

When an artificial fertilizer is replaced by biomass of algae, reed, and mussels indirect energy benefits arise. The energy demands for production of artificial fertilizer per kg nitrogen (45 MJ) and per kg phosphorus (25 MJ), are received from the report of Berglund & Börjesson (2003)(see Table 9). In this thesis it is assumed that no corresponding energy cost arise from using biomass of algae, reed, and mussels as fertilizer. The energy demands are used to determine the indirect energy benefits when biomass corresponding to one tonne of nitrogen replaces artificial fertilizer. The energy savings are visualized as number of average Swedish households that annually can be heated from the corresponding energy, calculated as shown in Equation 32.

The number of average Swedish households that annually can be heated from indirect energy benefits from biomass corresponding to one tonne of nitrogen, H_{ieb}, was calculated as

$$H_{ieb} = ((1*E_{bN} + (1/\alpha_i)*\beta_i*E_{bP})*1000)/H_d \qquad (32)$$

Where $E_{bN,}$ and E_{bP} are energy demand from production of artificial fertilizer per kg nitrogen, and per kg phosphorus respectively. α_i = share nitrogen and β_i= share phosphorus, of algae, reed, and mussel wet weight respectively and H_d = heating demand of an average Swedish household.

2.11 Positive enironmental effects

With the purpose to find positive environmental effects as a result of the replacement of fossil fuels to biogas, the amount of CO_2 that can be saved from being released into the atmosphere was calculated. Data of annual CO_2 discharge from an oil heated household is used from Hägglund & Huring (2004) and amounts to 8 tonnes. The CO_2 discharge when net energy benefits from biogas production of biomass corresponding to one tonne of nitrogen replaces oil heating of Swedish average households was calculated in Equation 33. The net energy benefits are received from energy balances including a transport distance of 10 km and 100 km, respectively of biomass corresponding to one tonne of nitrogen as shown in Equation 29.

The CO_2 discharge when net energy benefits from biogas production of biomass corresponding to one tonne of nitrogen, E_{b_ij}, replaces oil heating of Swedish average households, D_{b_i}, was calculated as

$$D_{b\_i} = H_{b\_ij} * D \qquad (33)$$

Where D is CO_2 discharge from an oil heated household (i.e. i = algae, reed, and mussels and j = 10 km and 100 km).

2.12 Suitability as fertilizer

In order to investigate the suitability as fertilizers, the relationships between different nutrients (i.e. nitrogen, phosphorus, and potassium) of the three biomasses where compared to nutrient sufficiency of crops from a report of Davidsson (2007). The nutrient contents in the report where given as quotients of nitrogen (see Table 11).

Table 11. Nutrient sufficiency of crops as quotients of nitrogen.

Peas [N:P:K]	Grain [N:P:K]	Sugar beets [N:P:K]
1:0.11:0.28[a]	1:0.10:0.49[a]	1:0.17:1[a]

[a]Davdisson, 2007

3 Results

3.1 Biomass content of nutrients and volatile solids

The wet weight nutrient contents (i.e. nitrogen and phosphorus) of algae, reed, and mussels are shown in Figure 3.1.1. Dry weight as percentage of wet weight, the content of volatile solids as percentage of dry weight and wet weight of algae, reed, mussels, and sludge are shown in Figure 3.1.2. The contents as percentage of wet weight of the three biomasses were calculated in Equations 1-2. The wet weight nutrient content is higher for mussels compared to algae and reed. The wet weight nitrogen content of mussels is over three times higher than that of algae and reed. The wet weight phosphorus content of mussels is over two times higher than that of algae and reed (see Figure 1.1).

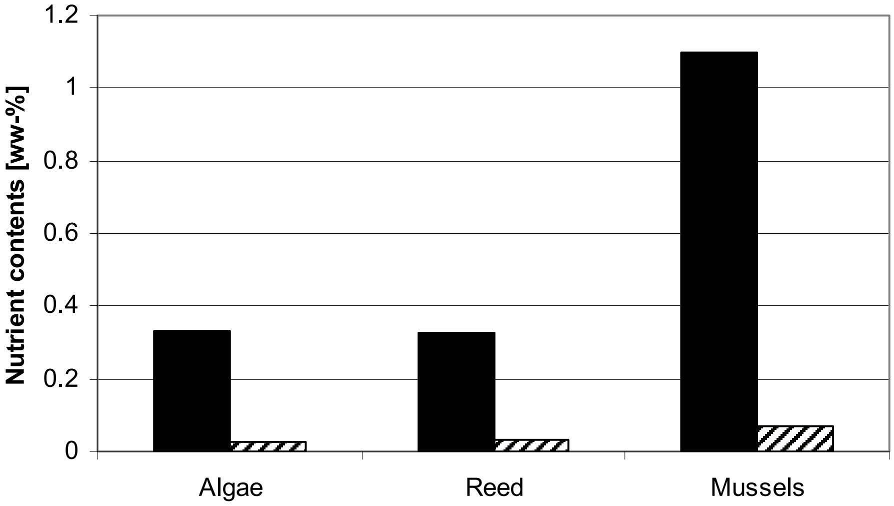

Figure 3.1.1. Wet weight nutrient contents [%] of algae, reed, and mussels where the bar to the left (black) represents nitrogen and the bar to the right (striped) represents phosphorus.

The dry weight volatile solid content of reed exceeds 90 % followed by mussels, sludge, and algae of 86 %, 68 %, and 65 % respectively (see Figure 3.1.2). Due to higher wet weight dry weight content of reed compared to mussels, sludge, and algae, i.e. 17, 8, and 3 times higher, the differences with respect to wet weight volatile solid content increase even more. The wet weight volatile solid content of reed is 19, 11 and 4 times higher compared to mussels, sludge and algae respectively (see Figure 3.1.2).

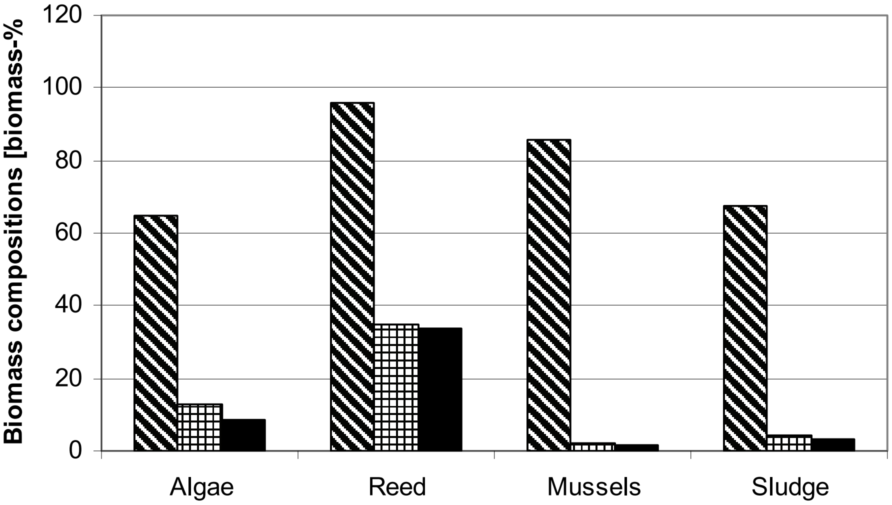

Figure 3.1.2 . Wet weight dry weight-, dry weight volatile solid-, and wet weight volatile solid contents of algae, reed, mussels, and sludge. The bar to the left represents dry weight volatile solid content, the intermediate bar represents wet weight dry weight content and the bar to the right represents wet weight volatile solid contents of algae, reed, mussels, and sludge.

3.2 Nutrient amounts and areas

3.2.1 Nutrient amounts

In order to achieve good ecological status of the Baltic Sea in the year of 2021, an action plan has been created by the Helsinki Commission (HELCOM) (Miljödepartementet, 2008). According to the action plan, 21 000 tonnes of nitrogen and 290 tonnes of phosphorus shall be decreased of the annual discharge from Sweden. The working hypothesis of this work is that Ecological engineering methods can considerably help meeting these environmental goals through the harvest of algae, reed and/or mussels along the Swedish Baltic coastline. The potential amount of algal biomass that annually can be harvested from the Swedish south coast, that reaches from Malmö to Simrishamn amounts to approximately 330 000 tonnes of wet weight (see Figure 3.2.1). This potential amount of algal biomass corresponds to 1100 tonnes of nitrogen and 91 tonnes of phosphorus (see Figure 3.2.2), which corresponds to 5 % nitrogen and 31 % phosphorus of the amounts of the action plan (see Table 3.1.1).

As there is no documentation of the potential biomasses of reed and mussels that annually can be harvested form the Baltic coastline of Sweden, the potential amount of nitrogen harvested through algae (i.e. 1100 tonnes) is used as a comparative measure in this work. The biomass (i.e. wet weight) of reed and mussels that need to be harvested in order to achieve the same amount of nitrogen amounts to 330 000 and 100 000 tonnes of wet weight, respectively (see Figure 3.2.1), calculated from data of wet weight nitrogen content in Equation 4. The amount of phosphorus in the corresponding biomass is 105 tonnes for reed and 70 tonnes for mussels (see Figure 3.2.2). The biomasses of reed and mussels that correspond to 1100 tonnes nitrogen and the phosphorus contents of the biomasses are calculated from data of wet weight nitrogen and phosphorus contents in Equation 5.

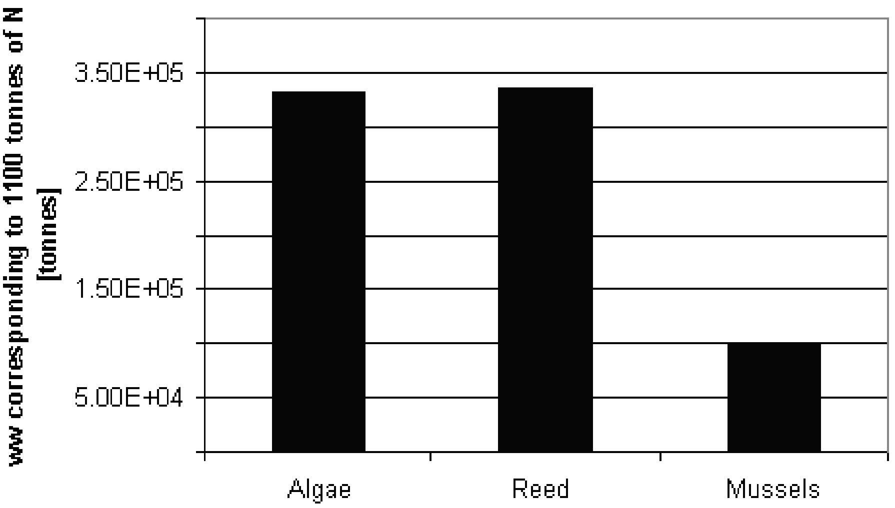

Figure 3.2.1 Wet weight of biomass of algae, reed, and mussels [tonnes] corresponding to 1100 tonnes of nitrogen (i.e. used as a comparative measure in this work) respectively.

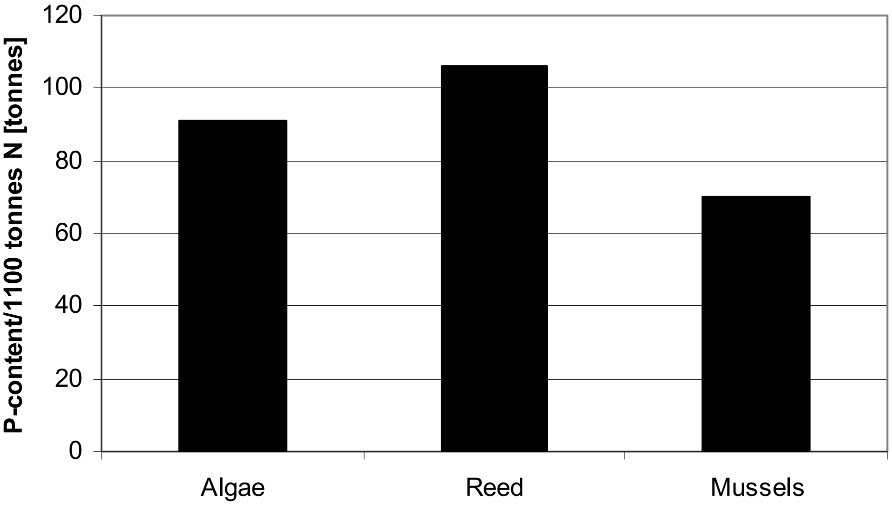

Figure 3.2.2 Phosphorus content of biomass of algae, reed mussels [tonnes] corresponding to 1100 tonnes nitrogen respectively.

Table 3.2.1 1100 tonnes of nitrogen and corresponding amounts of phosphorus (i.e. of algae, reed, and mussel biomass respectively) as percent of the nutrient amounts of the action plan

	Nitrogen	Phosphorus
Nutrient amount according to the action plan [tonnes]	21 000[a]	290[a]
Algae [i] [%]	5.0	31
Reed [ii] [%]	5.0	36
Mussels [iii] [%]	5.0	24

[a] Miljödepartementet, 2008

i. On the Swedish South coast
ii. Along part of the Baltic coast line of Sweden
iii. Part of the water area of the Stockholm archipelago

3.2.2 Areas

The area of reed that needs to be harvested and the water area that need to be covered with mussel farms in order to reduce 1100 tonnes of nitrogen from the Baltic coast line of Sweden annually, amounts to 12 000 hectares and 1700 hectares respectively. The areas were calculated by using data of amount of reed per hectare, the area and amount of biomass per mussel farm and the concentration of nitrogen of the three biomasses (see

Equations 6-7). There is no documentation of potential biomasses of reed and mussels that annually can be harvested from the Baltic coast line of Sweden. In order to appreciate the realism of the calculated areas, they were compared to Swedish total reed area of 100 000 hectares and the water area of the Stockholm archipelago of 372 500 hectares (collected from reports of Hansson & Fredriksson (2004) and Nordiska ministerrådet (2009)). The areas of reed and mussels respectively, were calculated as proportions of the areas in Equation 8. The result showed that the areas, in order to annually reduce 1100 tonnes of nitrogen, correspond to 11.7 % of Swedish total reed area and 0.45 % of the water area of the Stockholm archipelago (see Table 3.2.1).

Table 3.2.2 Areas to harvest biomass equivalent to 1100 tonnes of nitrogen of reed and mussels, respectively, and the areas as percent of Swedish total reed area and of the water area of the Stockholm archipelago.

	Area [ha]	share [%]
Reed	12 000	11[i]
Mussels	1 700	0.45 [ii]

i. of Swedish total reed area
ii. of the water area of the Stockholm archipelago

LCI

In order to determine the biogas potential of biomasses of algae, reed, and mussels, LCI has been made which extends from the harvest (i.e. from the Baltic coast of Sweden) to the production of biogas. Energy balances have been calculated from the LCI, where energy demands were subtracted from energy benefits regarding biomass corresponding to one tonne of nitrogen (i.e. of algae, reed, and mussels respectively). The energy benefit represents the potential of methane extraction of the three biomasses and the energy demands include harvest, transportation from the harvest spot to the biogas plant and heating- and electricity demands from the biogas production process. The energy benefits and the energy demands are further described in Chapters 3.3 and 3.4. In Chapter 3.5 energy demands in relation to energy benefits are presented and Chapter 3.8 contains energy balances.

3.3 Energy benefit

The energy potential of biomass from algae, reed, and mussels was calculated from data of liter CH_4 that can be extracted per kg volatile solids in Chapter 2.3. The energy potential of biomass depends on factors such as share of volatile solids of the biomass and how well suited the organic matter of the volatile solids is as substrates for the microorganisms in the biogas production process. Figure 2.3.1 presents the energy potential per tonne of volatile solids, dry weight, and wet weight, respectively, for the three biomasses and sludge in order to appreciate the biogas potential in comparison to a reference (see Equations 9-12).

The energy content per tonne volatile solids is highest in mussels, i.e. 1.4 times higher than in sludge and 4-5 times higher than in reed and algae. The relative order of the substrates based on energy content per tonne dry weight is similar to those of volatile solids i.e. 2, 4, and 6 times higher of mussels than that of sludge, reed, and algae respectively, (even though the dry volatile solid content of mussels is lower compared to reed, see Figure 3.1.2). The energy content per tonne wet weight is between 3 and 4 times higher in reed compared to the other substrates (see Figure 3.3.1), this is due to high wet weight volatile solid content of reed, i.e. 18, 11, and 4 times higher than that of mussels, sludge, and algae respectively (see Figure 3.1.2).

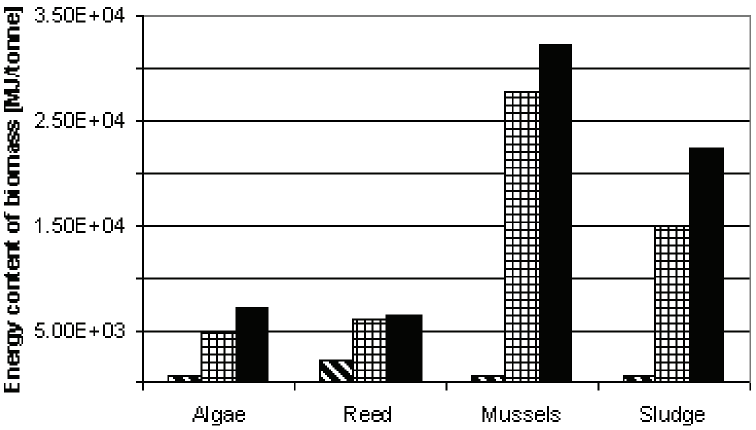

Figure 3.3.1 Energy benefit per tonne wet weight, dry weight, and volatile solids of algae, reed, mussels, and sludge respectively. For the four substrates, the bar to the left represents energy potential per tonne wet weight, the intermediate bar represents energy potential per tonne dry weight and the bar to the right represents energy potential per tonne volatile solids.

The energy benefit of reed is superior compared to that of algae and mussels and shows 4 and 13 times higher value compared to algae and reed respectively (see Figure 3.3.2). The wet weight nitrogen content of reed and algae is similar (0.3 %), and therefore corresponds to similar amounts of biomass (for nitrogen content of wet weight, see Figure 3.1.1). The reason why the energy benefit of reed still is higher is the higher energy potential per tonne biomass compared to algae (see Figure 3.3.1).

The nitrogen content of mussels is three times higher compared to algae and reed, and a smaller amount of biomass of mussels corresponds to one tonne of nitrogen compared to algae and reed (for nitrogen content of wet weight, see Figure 3.1.1), another factor is that algae and reed have higher energy benefit per tonne wet weight compared to mussels (see Figure 3.3.1). The number of Swedish average households that annually can be heated from the biogas benefit from biomass including one tonne of nitrogen is 3.0, 12 and 1.0 of algae, reed, and mussels respectively (see Table 3.3, Equations 13-14)

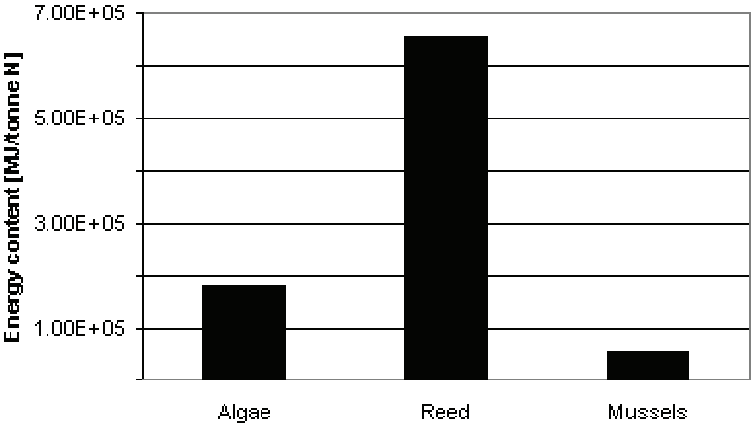

Figure 3.3.2 Energy potential of biomass equal to one tonne of nitrogen.

3.4 Energy demands

3.4.1 Harvest

The harvest technique of algae and reed is different from the one of mussels and the energy demand per tonne biomass (i.e. wet weight) is almost 11 and 13 times higher for mussels compared to algae and reed respectively, as shown in Figure 3.4.1. The energy demand for biomass corresponding to one tonne of nitrogen is three and four times higher for mussels compared to algae and reed, respectively (see Table 3.4.2). The differences between mussels and the other two biomasses decrease due to the over three times higher nitrogen content of mussels compared to algae and reed (i.e. a smaller amount of mussel wet weight need to be harvested in order to receive the same amount of nitrogen). Both energy demand per tonne wet weight and for biomass including one tonne of nitrogen are similar for algae and reed, due to similar wet weight content of nitrogen (for nitrogen content of wet weight, see Figure 3.1.1, see Equations 15-24).

3.4.2 Transport

The energy demand per 10 km for transportation per tonne biomass (i.e wet weight of algae, reed and mussels, respectively) amounts to 27 MJ. The energy demand per 10 km for transportation of biomass of one tonne wet weight and including one tonne of nitrogen respectively, is presented in Figure 3.4.1 and 3.4.2 (for calculations of energy demand from transport, see Equation. 25-26). The energy demand for biomass including one tonne of nitrogen is more than three times lower for mussels than for algae and reed. This is due to the over three times higher nitrogen content of mussels compared to algae and reed (i.e. less biomass need to be transported in order to achieve the same amount of nitrogen). The energy demand for algae and reed are similar due to similar wet weight content of nitrogen (for nitrogen content of wet weight, see Figure 3.1.1). Depending on the location of the harvesting point and of the nearest biogas plant, the transport distance of the biomass varies. In order to visualize the influence of energy demand with regard to transport distances, energy balances including energy demands for different transport distances are presented in Chapter 3.5.

3.4.3 Heating- and electricity

Heating- and electricity demands occur in the biogas production process. Data for the demands as percentages of the energy content of biogas produced concerning a central biogas plant were received from the report of Berglund & Börjesson (2003). The energy demands were calculated as percentages of the energy content of biogas produced in Equation 27. Summarized demands from heating and electricity are shown for the three biomasses per tonne wet weight in Figure 3.4.1 and for biomass corresponding to one tonne nitrogen in Figure 4.2. The energy demand from heating and electricity from biogas production of one tonne wet weight is almost five times higher for reed than for algae and mussels respectively, as shown in Figure 3.4.1. The energy demand from heating and electricity from biogas production of biomass corresponding to one tonne of nitrogen is almost 4 times higher for reed compared to algae and almost 13 times higher for reed compared to mussels (see Figure 3.4.2).

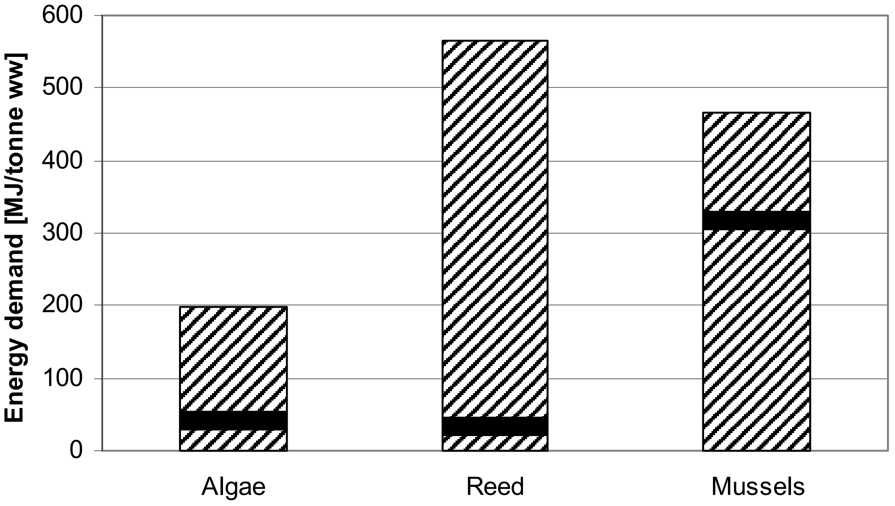

Figure 3.4.1. Energy demand [MJ $tonne^{-1}$ ww] where lower dashed area represents harvesting, intermediate black area represents transportation and upper dashed area represents biogas production for algae, reed and mussels.

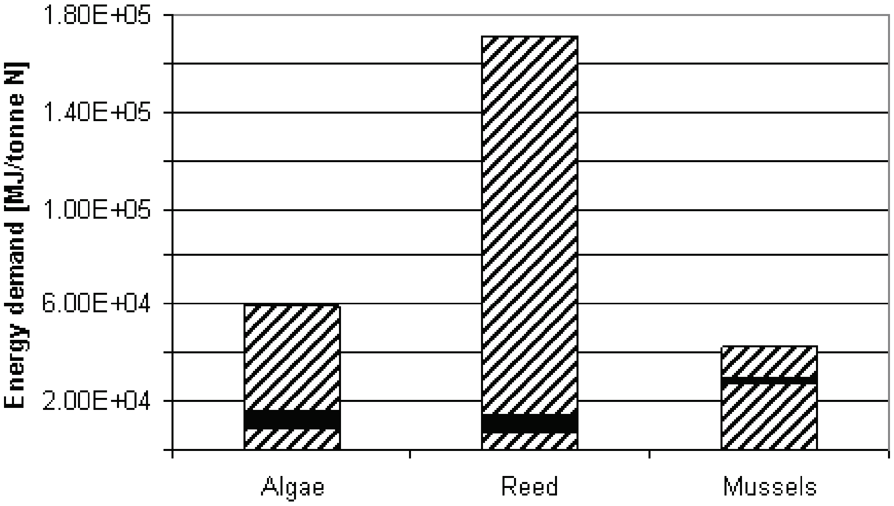

Figure 3.4.2 Energy demand [MJ $tonne^{-1}$ N] where lower dashed area represents harvesting, intermediate black area represents transportation and upper dashed area represents biogas production for algae, reed and mussels.

3.5 Energy balance

In the energy balances, energy demands are subtracted from energy benefits. The energy demands in the life cycle analysis include those related to harvest, transportation from the harvest spot to the biogas plant, and heating- and electricity demands in the biogas production. Depending on the location of the harvest spot and of the nearest biogas plant, the transport distance varies. In order to visualize the influence of energy demand according to transport distances, energy balances excluding energy demand from transport (i.e. including energy demand from harvest, heating and electricity) have been calculated. The net energy benefit, based on biomass corresponding to one tonne of nitrogen, is highest for reed , i.e. 42, and 4 times higher compared to mussels and algae, respectively (see Figure 3.5.1). In order to visualize the influence from transport distances, energy balances including transport distance of 10 km and 100 km are presented in Figure 3.5.2. From the positive net energy benefits of algae, reed, and mussels respectively, where a transport distance of 10 km has been included, 2.9, and 0.2 households can be heated respectively. When a transport distance of 100 km has been included, 1.0 and 8.0 households can be heated from algal and reed biomass respectively. The corresponding energy balance of mussels is negative (see Table 3.5, Equations 28-30).

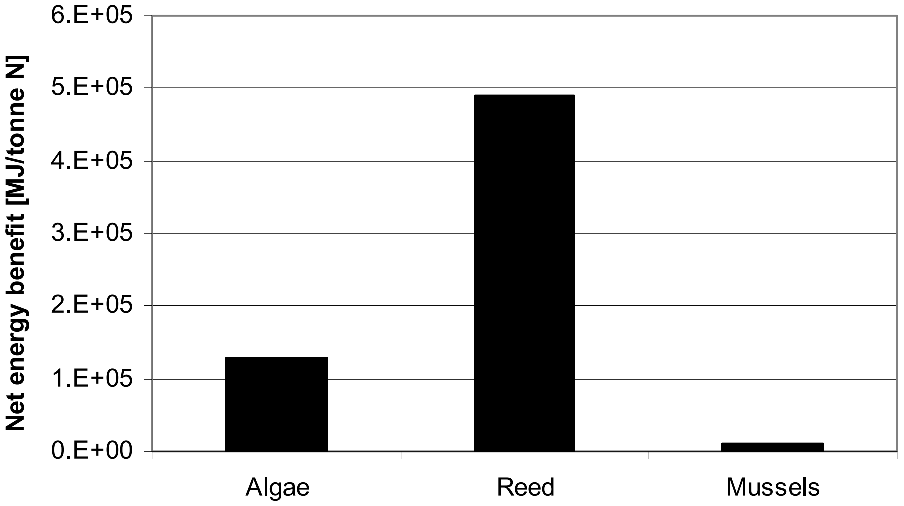

Figure 3.5.1 Energy balances excluding energy demand from transport (i.e. including energy demand from harvest, heating and electricity) for biomasses corresponding to one tonne of nitrogen of algae, reed and mussels.

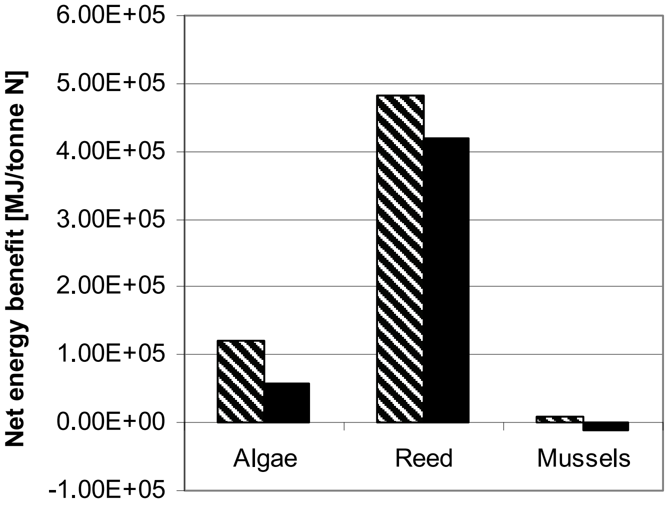

Figure 3.5.2 Energy balances for algae, reed and mussels including transport distances where the left bar represents demand of 10 km and the right bar of 100 km.

Table 3.5. Number of Swedish average households that can be heated from the positive net energy benefits from biomass including 1 tonne of nitrogen of algae, reed, and mussels respectively, including transport distances of 10 km and 100 km respectively (i.e. in Figure 3.5.2)

	Households (10 km)	Households (100 km)
Algae	2.0	1.0
Reed	9.0	8.0
Mussels	0.2	-

3.6 Transport distance from net energy benefits

Depending on location of the harvesting point and of the nearest biogas plant, the transport distance varies. The maximum distance that the biomass can be transported before the net energy benefit is used up was calculated as shown in Equation 31. No considerations have been taken to energy costs for upgrading of biogas to vehicle gas or manufacturing of other fuels used in the process (i.e. diesel) in the calculations.

The distance that biomass can be transported by using its corresponding net energy benefit is 670 km for reed, 180 km for algae, and 54 km for mussels. Figure 3.6.1 show the relationship between the net energy benefit (where energy demands from harvest, electricity- and heating have been subtracted from energy benefit) and the energy transport demand per km for reed. Where the two lines intersect, the value on the x-axis shows how far the biomass can be transported before the net energy benefit is consumed.

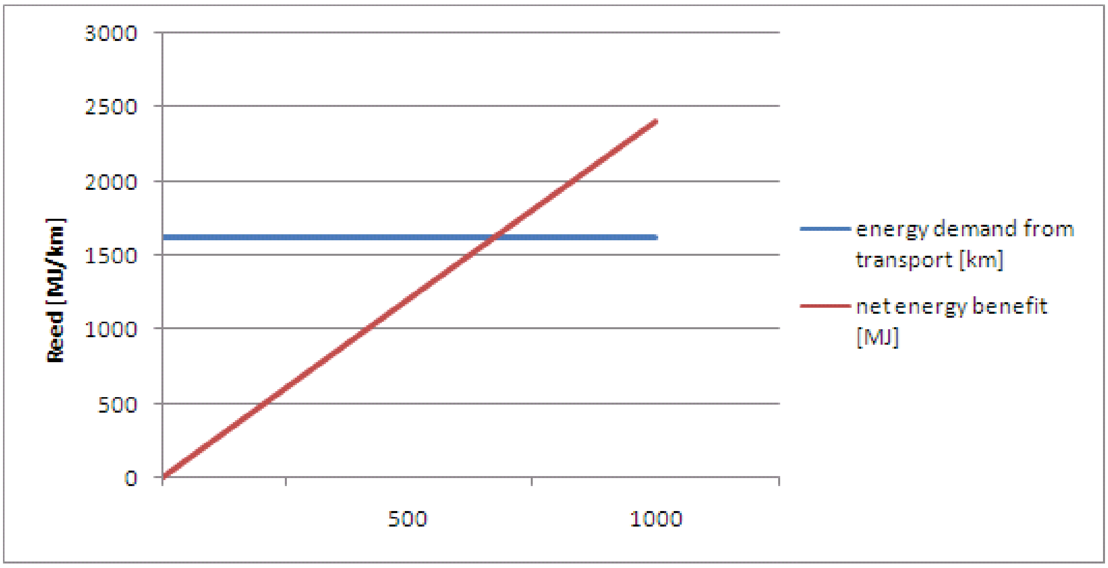

Figure 3.6.2 The relationship between the net energy benefit (per tonne wet weight where energy demands from harvest, electricity- and heating have been subtracted from energy benefit) and the energy transport demand per km for reed.

3.7 Indirect energy benefits

When artificial fertilizer is replaced by harvested biomasses of algae, reed, and mussels, indirect energy benefits arise. The biomasses are assumed to be ready for usage as fertilizer, without energy costs from manufacturing (unlike the case with artificial fertilizer). The energy demand for production of artificial fertilizer is 45 MJ per kg nitrogen and 25 MJ per kg phosphorus. Indirect energy benefits that follow replacement of artificial fertilizer to biomass corresponding to one tonne of nitrogen (i.e. used as a comparative measure in this work, see Chapter 3.2.1) and amounts of Swedish average households that annually can be heated were calculated in Equation 32. The energy benefit is slightly higher for reed followed by algae, and mussels, due to slightly higher phosphorus content per tonne nitrogen of reed. From biomass corresponding to one tonne of nitrogen, of algae, reed and mussels, respectively; approximately one household can be heated per year. Similar energy demands for transportation, and spreading on arable land of the biomasses and of an artificial fertilizer is assumed to occur.

3.8 Positive environmental effects

Positive environmental effects occur when biogas replaces fossil fuels because fossil CO_2 is then saved from being released into the atmosphere. Amounts of CO_2 that are saved if biogas from positive net energy benefits replaces oil heating of households have been calculated (see Equation 33). The estimations are done for biomass corresponding to one tonne of nitrogen from algae, reed, and mussels respectively (see Chapter 3.5). If biogas from net energy benefits of algae, reed, and mussels, would replace oil heating of households; 18, 72, and 1.4 tonnes of fossil CO_2 respectively, would be saved from being released into the atmosphere (i.e. from net energy benefit where a transport distance of 10 km is included). This corresponds to heating of 2.3, 9 and 0.2 households, respectively (see Table 3.8.1). The equivalent values if a transport distance of 100 km is included amounts to 8.5 tonnes and 62 tonnes of fossil CO_2, and heating of 1.0 and 7.8 households with regards to algae and reed, respectively (see Table 3.8.2). The net energy benefit of mussels is negative when a transport distance of 100 km is included in the energy balance, thus no estimation is made for mussels. In order to receive these results, the households where assumed to be heated with oil, no consideration is taken according to the CO_2 discharges during the life cycle of the corresponding fuels (i.e. biogas and oil).

Table 3.8.1: Fossil CO_2 saved from being released into the atmosphere per year if biogas from positive net energy benefits replaces oil heating of households. (I.e. positive net energy benefits where a transport distance of 10 km is included in the energy balance)

	Households	Tonnes of CO_2
Algae	2.3	18
Reed	9.0	72
Mussels	0.2	1.4

Table 3.8.2: Fossil CO_2 saved from being released into the atmosphere per year if biogas from positive net energy benefits replaces oil heating of households. (I.e. positive net energy benefits where a transport distance of 100 km is included in the energy balance)

	Households	Tonnes of CO_2
Algae	1.0	8.5
Reed	7.8	62
Mussels	-	-

3.9 Suitability as fertilizer in accordance with nutrient content

In order to assess the suitability of biomass of algae, reed and mussels as fertilizers according to contents of nitrogen, phosphorus, and potassium, the relationships between the nutrients (i.e. based on quotients of nitrogen) of the three biomasses where compared to nutrient sufficiency of crops from the report of Davidsson (2007). Table 3.9.1 shows nutrient sufficiency of peas, grain and sugar beets, and Table 3.9.2 shows nutrient contents in algae, reed and mussels. Comparison of the two tables show that there is a good potential of using all three biomasses as fertilizers with regards to the content of nitrogen, but the content of phosphorus occurs under the sufficiency levels of the crops. For algae and reed, the potassium contents occur above the level of peas and grain but under the level for sugar beets, for mussels the potassium content occurs under the sufficiency of all three crops.

Table 3.9.1 Nutrient sufficiency of crops (as quotients of nitrogen).

	N:P:K
Peas	1:0.11:0.28[a]
Grain	1:0.16:0.17[a]
Sugar beets	1:0.17:1[a]

[a]Davidsson, 2007

Table 3.9.2 Nutrient contents in algae, reed and mussels.

	N:P:K
Algae	1:0.10:0.49
Reed	1: 0.10:0.70
Mussels	1:0.06:0.10

Discussion

In order to achieve good ecological status of the Baltic Sea in the year of 2021, an action plan has been created by the Helsinki Commission (Miljödepartementet, 2008). According to the action plan, 21 000 tonnes of nitrogen and 290 tonnes of phosphorus shall be decreased of the annual discharge from Sweden. The working hypothesis of this work is that Ecological engineering methods can considerably help meeting these environmental goals through the harvest of algae, reed, and mussels along the Swedish Baltic coastline. The nitrogen and phosphorus content of mussels is almost three and two times higher compared to algae and reed respectively, which have similar nutrient contents (see Figure 3.1.1). Because of this fact, cultivation and harvesting of mussels are most effective in terms of nutrient reduction from the Baltic coast of Sweden, in comparison to harvest of algae and reed.

The potential amount of nutrients of algal biomass that annually can be harvested from the South coast showed, i.e. 5 % of nitrogen and 31 % of phosphorus respectively, can help meeting the nutrient goals of the action plan. The calculations of the potential amounts of algae from collection along the Southern coast of Sweden are made by Detox AB. The collection is assumed to take place in the water, with an area that reaches 100 meters out in the water from the coastline. The assumption of the quantities of algal biomass per hectare is based on the present collection performed by the municipality of Trelleborg (Barwén, 2009). Something that need to be carefully considered while harvesting algae is to restrict the harvesters from collecting important seaweed that create essential environments for other species. According to Jönsson (2001) a rich animal life exists in the algal mats, thus not only algae are collected during harvest but also the species living there.

While there are no documentations of potential biomasses of reed and mussels that annually can be harvested from the Baltic coastline of Sweden, the potential amount of nitrogen harvested through algae, i.e. 1100 tonnes of nitrogen have been used as a comparative measure in this work. The corresponding amount of phosphorus harvested through reed, and mussels, answers to 36 %, and 24 % respectively, of the action plan.

The harvestable areas of reed along the Swedish Baltic coastline in this work is an estimation based on data from the literature showing that reed grow as large, monospecific stands along the Baltic coast line of Sweden, and data of Swedish total reed area from report of Hansson & Fredriksson (2004). The areas suitable for mussel farming in the Swedish archipelago is based on data of the water area of the Stockholm archipelago from Svenska ministerrådet (2009) and conditions suitable for mussel farms (i.e. areas covered from wind and with certain depths from report of Lindahl *et al* (2005). In order to harvest 1100 tonnes of nitrogen through reed, 11 % of Swedish total reed area along the Baltic coastline of Sweden needs to be harvested. To harvest the same amount through mussels, 0.44 % of the water area of the Stockholm archipelago needs to be covered with mussel farms. The Swedish archipelago is a popular area for outdoor activities, and in order to determine which certain areas that can be covered with mussel farms, solutions need to be made locally. There are no documentations of the total reed area of the Swedish Baltic coastline (Granéli, 2008). The potential areas that can be harvested of the three biomasses from the Baltic coastline of Sweden need to be further investigated.

The harvesting technique of algae and reed studied in this work is the Aquatic Plant Harvester, RS 2000, a floating device suitable for harvest of water plants (RS Planering AB, 2008). A floating device is preferable for harvest of reed, because it prevents the rhizome from being damaged (Hansson & Fredriksson, 2004). The fast growing vegetation, important for fish species, is easily damaged by land based harvesting techniques (Heikkilä & Mattila, 2000). Long line mussel farming is a farming technique developed in Sweden and is beneficial in comparison to bottom scraping (Sanchez *et al*, 2004). A drawback with the mussel farms is that the sediment underneath the farm can be overloaded and increased sedimentation can give rise to decreased oxygen concentrations underneath the farms. But these negative effects only occur locally and the overall positive environmental effects need to be considered (Lindahl *et al*, 2005).

LCI which reaches from the harvesting of biomass to the production of biogas have been created in order to determine the biogas potential of the three biomasses. The energy demand in the process represents the demands from harvesting, transportation from harvest location to a central biogas plant, heating, and electricity demands from the biogas production process. The energy benefit represents the potential methane extraction of the biomasses.

Mussels contain the highest amount of energy per tonne volatile solids, 1.4 times higher than sludge and between 4 and 5 times higher than algae and reed, respectively (see Figure 3.3.2). Even though the dry weight volatile solid content is highest in reed (followed by mussels, sludge, and algae, see Figure 3.1.2) the energy dry weight content of mussels is higher (see Figure 3.3.1).

With respect to wet weight, reed contains most energy, i.e. between 3 and 4 times higher compared to sludge, algae, and mussels respectively (see Figure 3.3.1). This is due to superior wet weight volatile solid content of reed, i.e. 18, 11, and 4 times higher, compared to mussels, sludge, and algae, respectively (see Figure 3.1.2).

The chemical composition of the substrates has influence on the biogas production (Berglund & Börjesson, 2003). The nitrogen content of mussels is higher compared to the other biomasses. In the degradation process, organically bound nitrogen is transformed to ammonia, which has an inhibitive effect on the microorganisms (Nilsson, 2000). Lignin, which increases in reed biomass in the autumn is hard to digest in the biogas process (Eno, 2007), in order to achieve a greater amount of methane from reed, harvest before autumn is to prefer.

The energy demand from transport is the same for the three biomasses, the transport distance varies depending on the location of the biogas plant and of the harvesting point, in this study 10 km is used for simplicity (see Figure 3.4.1). The same technique is used to harvest algae and reed and therefore, similar energy demands occur (see Figure 3.4.1). It is normally less time consuming to collect algae than reed, because, unlike reed, algae do not cover the whole water surface (Salin, 2008).

The energy demand of mussels is higher due to a more energy demanding harvesting process (Granhed, 2009). In reality, the harvest demand in the LCI varies depending on transport distances (i.e. between harvest location and shore) and occurrence of biomass.

The heating- and electricity demands in the biogas production process is calculated as share of the energy content received, and is therefore proportional to energy contents of the three biomasses, i.e. between three, and four times higher of reed than that of algae, and mussels respectively (see Figure 3.4.1). The assumption that the energy demands are proportional to the energy content in the biogas produced is simplifying. In reality these demands depend on substrate composition etc. The electricity demand depend on the substrates requirement of milling, cutting, pumping, and stirring, etc and the heating demand on the necessity of heating and hygienization (Berglund & Börjesson, 2003).

Depending on the location of the harvesting area and of the biogas plant, the transport distance varies. The net energy benefit excluding transport demand, according to energy balances based on biomass corresponding to one tonne nitrogen, is the highest for reed , i.e. 42, and 4 times higher compared to mussels and algae, respectively (see Figure 3.5.1). The maximum distance that the biomass of algae, reed, and mussels can be transported before the net energy benefit is used up is 670 km, 180 km, and 54 km respectively.
In order to visualize the influence from transport distances, energy balances including transport distance of 10 km and 100 km are presented in Figure 3.5.2. According to these results, potential occurs of further investigation concerning reed and algae. The suitability of reed as substrate in biogas production is also documented in the study of Hansson & Fredriksson (2004). The low net energy benefit of mussels shows that mussels are not a suitable substrate for biogas production. According to Lindahl *et al* (2005) an alternative is to use mussels (i.e. instead of fish meal) in chicken feed.

When biogas replaces fossil fuels, positive environmental effects occur because fossil CO_2 is then saved from being released into the atmosphere. From the positive net energy benefits of reed biomass (i.e. corresponding to one tonne of nitrogen) from energy balances including a transport distance of 10 km (see Figure 3.5.2), 72 tonnes of fossil CO_2 would be saved from being released to the atmosphere, which corresponds to heating of 9 Swedish households annually. The corresponding amounts that would be saved by algae and mussels are 18 and 1.4 tonnes respectively which equals heating of 2 and 0.2 households annually (see Table 3.8.1). In order to receive these results, the households where assumed to be heated with oil, release of fossil CO_2 from preparation of fuels is not taken into account (i.e. oil and biogas).

Indirect energy benefits that follow replacement of artificial fertilizer to biomass corresponding to equal amounts of nitrogen is slightly higher for reed followed by algae, and mussels. This is due to higher phosphorus content per tonne nitrogen of reed biomass. The indirect energy benefits correspond to annual heating of approximately one average Swedish household per biomass. There is a good potential of using all three biomasses as fertilizers regarding the content of nitrogen but the content of phosphorus occurs under the sufficiency levels of the crops. For algae and reed, the potassium contents occur above the level of peas and grain but under the level of sugar beets. Regarding mussels the potassium content occurs under the sufficiency of all three crops (see Tables 3.9.1 and 3.9.2).

A limiting factor in the usage of fertilizer is the biomass content of heavy metals, i.e. Cadmium. Cd is a heavy metal that accumulates in the ground and is therefore available for plants a long time after its supply (Davidsson, 2007). Results from Davidsson (2007) show that algal content of all heavy metals, except for Cd, occur far below the limiting values and Olrog & Christensson (2003) show similar results for mussels. In comparison to other water plants, reed is a pure substrate, with low heavy metal contents, and is suitable as fertilizer on arable land, according to Fredriksson (2002). Methods to remove heavy metals exist. One drawback that can occur is loss of organic material while purifying the biomasses from Cd, which will have negative impacts on biogas potential of the biomasses (Davidsson & Ulfsdotter Turesson, 2008, Melin, 2001).

Conclusion

An action plan has been created by the Helsinki Commission (HELCOM) in order to achieve good ecological status of the Baltic Sea in the year of 2021. According to the action plan, 21 000 tonnes of nitrogen, and 290 tonnes of phosphorus shall be decreased of the annual discharge from Sweden. Methods within ecological engineering can help meeting the environmental goals through the harvest of algae, reed, and mussels considerably, both regarding areas and amounts that need to be harvested along the Swedish Baltic coastline.

While there are no documentations of potential biomasses of reed and mussels that annually can be harvested from the Baltic coastline of Sweden, the potential amount of nitrogen harvested through algae from the Swedish south coast, i.e. 1100 tonnes, have been used as a comparative measure in this work. The calculation of the algal biomass is based on an assumption that the algae are collected from the water within an area that reaches 100 metres out from the coastline (i.e. between Malmö and Simrishamn) and assumptions of the quantities of algal biomass per hectare is based on the present collection performed by the municipality of Trelleborg (Barwén, 2009). The potential amount of nutrients of algal biomass that annually can be harvested from the South coast corresponds to 5 % of nitrogen and 31 % of phosphorus respectively, of the total reduction in the action plan (see Table 3.2.1).

In order to harvest 1100 tonnes of nitrogen through reed, 11 % of the Swedish total reed area along the Baltic coastline of Sweden needs to be harvested. To harvest the same amount through mussels, 0.44 % of the water area of the Stockholm archipelago needs to be covered with mussel farms (see Table 3.2.2). These areas are estimations based on data of the Swedish total reed area, and of the water area of the Stockholm archipelago. In order to determine the potential amounts of the three biomasses that annually can be harvested from the Baltic coastline of Sweden, further investigations about occurrence, disturbance of ecosystems associated to harvest, and disturbance of outdoor life (i.e. covering of mussel farms in recreational areas) are needed.

Farming and harvesting of mussels is most efficient based on wet weight as regards nutrient reduction from the Baltic coastline of Sweden, in comparison to harvest of algae and reed. The nitrogen and phosphorus contents of mussels are almost three, and two times higher compared to algae and reed, respectively (see Figure 3.1.1).

In order to investigate the biogas potential of the three biomasses LCI, which extends from the harvesting of biomass to the production of biogas has been created. The energy benefit is represented by the potential methane extraction of each biomass (see Figure 3.3.1). The energy demand in the process includes the demands from harvest, transportation from harvest location to a central biogas plant and heating and electricity demands in the biogas production process (see Figure 3.4.1). In reality, the transport distance varies depending on location of harvest area and of the biogas plant. The harvesting energy demand in the LCI varies with transport distances (i.e. between harvest and shore) and occurrence of biomass. In this study, it is assumed that the energy demands are proportional to the energy content in the biogas produced, which is a simplification. In reality these demands depend on substrate composition and on the design of the biogas plant.

According to the energy balances, based on biomass corresponding to one tonne of nitrogen, reed has the highest net energy benefit followed by algae. Mussels showed to have low net energy benefit (see Figure 3.5.1). The conclusion is that biogas production from reed and algae has a positive potential and is worthy of further investigation, and that mussels are not a suitable substrate in biogas production.

Mussels have potential of being used in chicken feed (i.e. instead of fish meal) according to Lindahl *et al* (2005), as an alternative product. Another product that possibly can be received from the harvested biomasses is fertilizer, the study shows that all three biomasses have potential regarding the nutrient content of nitrogen but the content of phosphorus occurs under the sufficiency levels of the crops investigated (i.e. peas, grain, and sugar beets). For algae and reed, the potassium contents occur above the level of peas and grain but under the level of sugar beets, for mussels the potassium content occurs under the sufficiency of all three crops (see Tables 3.9.1 and 3.9.2).

Cd is a limiting factor of using the biomasses as fertilizers on arable land. While it accumulates in the ground, it is difficult to investigate the biomasses suitability as fertilizer regarding Cd. In order to draw more accurate conclusions, i.e. regarding heavy metal contents, closer studies need to be performed.

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Appendix

Equation symbols

Chapter 2.1

Nw_{ij} = wet weight nutrient proportions (i.e. N and P) of algae, reed, and mussels respectively

Nd_{ij}= dry weight nutrient contents (i.e. nitrogen and phosphorus) of algae, reed, and mussels respectively

α_i= wet weight nitrogen proportion of algae, reed, and mussel respectively

β_i= wet weight phosphorus proportion of algae, reed, and mussel respectively

γ_i= wet weight dry weight proportion of algae, reed, mussel, and sludge respectively

δ_i = dry weight volatile solids proportion of algae, reed, mussels, and sludge respectively

ε_i = wet weight volatile solids proportion of algal, reed, mussel, and sludge respectively

Chapter 2.2.1

y,n_{algae} = Contents of nitrogen [tonnes] of potential biomass that annually can be harvested from the Swedish south coast

y,p_i = Contents of phosphorus [tonnes] of algal, reed, and mussel biomass corresponding to 1100 tonnes of nitrogen respectively

w_{algae} = corresponding wet weight of potential biomass that annually can be harvested from the Swedish south coast

wn,i= amount of mussel and reed wet weight [tonnes] corresponding to 1100 tonnes of nitrogen respectively

Chapter 2.2.2

N_i= nitrogen content per hectare of reed, and mussel biomass respectively

B_i = wet weight per hectare of reed and mussels, respectively

A_{reed} = area of reed that need to be harvested in order to annually reduce 1100 tonnes of nitrogen

$A_{mussels}$ = water area that need to be covered with mussels in order to annually reduce 1100 tonnes of nitrogen
S_{reed} = share of Swedish total reed area that need to be harvested in order to reduce 1100 tonnes of nitrogen from the Swedish Baltic coastline annually
$S_{mussels}$ = share of the water area of Stockholm's archipelago that need to be covered with mussel farms in order to reduce 1100 tonnes of nitrogen from the Swedish Baltic coastline annually
T_{reed} = Swedish total reed area
$T_{mussels}$ = The water area of Stockholm's archipelago

Chapter 2.4
$\iota_{mussels}$ = energy potential as liter CH_4 per kg wet weight of mussels
κ_i = energy potential as liter CH_4 per kg volatile solids of algae, reed, mussels, and sludge respectively
λ = MJ/l CH_4
μ_{vs_i} = MJ/tonne volatile solids of algae, reed, mussels, and sludge respectively
μ_{dw_i} = MJ/tonne dry weight of algae, reed, mussels, and sludge respectively
μ_{ww_i} = MJ/tonne wet weight of algae, reed, mussels, and sludge respectively
μ_{N_i} = MJ/ biomass corresponding to one tonne of nitrogen of algae, reed, and mussels respectively
H_d = heating demand of an average Swedish household
H_b = Number of Swedish average households that annually can be heated from the energy benefit of biomass corresponding to one tonne of nitrogen

Chapter 2.5
h_{day} = hours per working day
ν_i= hectares harvested per hour of algae, and reed respectively
ν_{day_i}= hectares harvested per day of algae, and reed respectively
ξ_i = tonnes of wet weight harvested per hour of algae, and reed respectively
ξ_{dw_reed} = tonnes of dry weight per hectare of reed

ξ_{day_i} = tonnes of wet weight harvested per day of algae, and reed respectively

ξ_{N_i} = tonnes of nitrogen harvested per day of algae, and reed respectively

Chapter 2.5.1

E_{rs2000} = Energy demand per working day with RS 2000

E_{ww_i} = Energy demand per tonne algal, reed, and mussel wet weight harvested respectively

Chapter 2.5.2

E_{l-l} = Energy demand from harvest of a long-line mussel farm including transport

ξl-l = tonnes of mussel wet weight per long-line mussel farm

ξ_{l-l_N} = Tonnes of nitrogen harvested per long-line musself farm

E_{N_i} = energy demand to harvest biomass corresponding to one tonne nitrogen of algae, reed, and mussels respectively

Chapter 2.6

ρ_{ww} =Dry weight of 30 % transformed to its corresponding wet weight

$\varsigma_{\_i}$ = Energy demand from transporting biomass per tonne a distance of 10 km, and 100 km respectively

ς = energy demand per tonne of dry weight per km

ςs = energy demand as share of energy content

$\varsigma_{N\ \_ij}$ = Energy demand from transport biomass (i.e. of algae, reed, and mussels respectively) corresponding to one tonne of nitrogen 10 km and 100 km respectively

Chapter 2.7

D_{eh} = energy demand from electricity and heating in the biogas process as share of energy content of biogas produced

D_{eh_i} = energy demand from heating and electricity in the biogas process of biomass of algae, reed, and mussels corresponding to one tonne of nitrogen respectively

Chapter 2.8

E_b = Energy balance excluding energy demand from transport

E_{b_i} = Energy balance including transport distance of 10 km, and 100 km respectively

H_{b_ij} = Number of Swedish households that can be heated from positive net energy benefits from energy balances including transport distances of 10 km and 100 km (i.e. where i = 10 km and 100 km and j = algae, reed, and mussels)

Chapter 2.9

D_{net} = The distance that biomass can be transported before its positive net energy benefit is consumed

ς_{N_1km} = energy demand from transportation of biomass per km

Chapter 2.10

H_{ieb} = The number of average Swedish households that annually can be heated from indirect energy benefits from biomass corresponding to one tonne of nitrogen

E_{bi} = Energy demand for production of artificial fertilizer per kg nitrogen, and phosphorus respectively

Chapter 2.11

D = CO_2 discharge from an oil heated household

D_{b_i} = The CO_2 discharge when net energy benefits from biogas production of biomass corresponding to one tonne of nitrogen, E_{b_i}, as deduced above, replaces oil heating of Swedish average households (i.e. where i = algae, reed, and mussels).

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