Life cycle assessment of macroalgae cultivation and processing for biofuel production

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SUPPLEMENTARY INFORMATION

Supplementary data A – Life cycle inventory

I. Biomass production

Values for the biomass production rate for each scenario were obtained from published material largely based on experimental work conducted around the south of Chile (Buschmann et al. 1995; Buschmann et al. 2008). *Gracilaria chilensis* and *Macrocystis pyrifera* naturally have a different growth rate depending upon cultivation method, location, climate and nutrient availability among many other factors. An upper and lower value of productivity for each cultivation scenario was obtained from published studies with a median value providing the value for the base case. Where the obtained values were presented as fresh weight, a moisture content of 85% was assumed (Bruton et al. 2009). For long-line cultivation, a space of 2 m was assumed between lines corresponding to a rope length of 5 km per hectare.

The values for Scenario 1, the bottom cultivation of *G. chilensis* assumed sub-tidal cultivation between a depth of 0.75 m and 2.5 m, the lower value being recorded at a depth of 0.75 m and the highest value at 2.5 m in the south of Chile (Buschmann et al. 1995). The values for Scenario 2 were obtained from two studies both of which considered the potential of the cultivation to remove nutrients from nearby salmon farms. A lower value (1.68 kg/m/month) was recorded on a line grown adjacent to a salmon farm over the summer months. An upper value of 2.8 kg/m/month was recorded over the spring months in southern Chile (Buschmann et al. 2008), similarly influenced by a salmon farm. The upper yield for Scenario 3 was taken from the same study where a *M. pyrifera* yield of 25 kg/m was recorded over a period of 9 months. The lower yield was taken from a study in the north of Chile where a yield of 22 kg/m was recorded after 120 days of off-shore cultivation (Macchiavello et al. 2010).

The carbon dioxide (CO_2) uptake of each process stream was calculated as the carbon contained within the fertiliser produced. The carbon contained within the fertiliser was calculated based on the elemental carbon content of the species. The carbon content varies between species but a value of 30% was assumed for both species which is a typical value for macroalgae on a dry weight basis (Chung et al. 2011). Based on the stoichiometry of CO_2, for every kg of C produced 3.67 kg of CO_2 was assumed to be taken from the environment.

II. Biofuel production

Values for biofuel yields were taken from a variety of published experimental studies, using the same method as used for the productivity, an upper and lower value were obtained with the median providing the base case.

II.1. Bioethanol production

The research that has been conducted on the conversion of macroalgae to bioethanol is limited to a few species, mainly brown algae (Adams et al. 2009; Adams et al. 2011; Wargacki et al. 2012). Since ethanol yields from *G. chilensis* are currently not available in the literature, yields from other *Gracilaria* species were used instead. The lower yield considered in the study was obtained from an experimental study that achieved a yield of 3.6 kg ethanol/kg biomass (d.w) from *Gracilaria verrucosa* (Kumar et al. 2013), a higher yield of 7.9 kg ethanol/kg biomass (d.w) was obtained from *Gracilaria salicornia* (Wang et al. 2011) using acid and enzymatic hydrolysis followed by fermentation with *Escherichia coli* to produce ethanol.

Ethanol production rates from *M. pyrifera* have not been studied, data from alternative brown macroalgae species were therefore substituted. A lower yield of 10.86 kg ethanol/kg biomass (d.w) was obtained from an experimental study where *L. japonica* was fermented using the yeast, *Debaryomyces occidentalis* (Lee and Lee 2012). A higher value of 13.2 kg ethanol/kg biomass (d.w) was obtained from a study considering the hydrolysis and fermentation of *Laminaria digitata* using laminarinase for hydrolysis and *Pichia angophorae* for fermentation (Adams, Toop et al. 2011).

II.2. Biogas production

Biogas yields obtained were provided as litres of CH_4 per gram of volatiles solids (VS) of dried biomass, the volatile solids content for *G. chilensis* and *M. pyrifera* is 59% for both, taken as an average from Habig et al. (1984) and Roesijadi et al. (2010), respectively. Values based on a study using *Gracilaria sp.* (Habig et al. 1984) were used for the upper yield of biogas production where a mesophilic temperature of 32°C and retention time of 58 days produced a yield of 0.23 L CH_4/g VS. A lower yield of 0.18 L CH_4/g VS was obtained from an experimental study using a temperature of 37°C and a retention time of 82 days (Costa et al. 2012) . The range of the upper and lower value of *M. pyrifera* was greater with a lower yield of 0.20 L CH_4/g VS and an upper yield of 0.41 L CH_4/g VS both produced under mesophilic conditions (Chynoweth et al. 2001).

II.3. Combined production of bioethanol plus biogas

The dry mass of stillage from the fermentation and distillation process was calculated by subtracting the ethanol and CO_2 produced from the initial biomass. CO_2 emitted during the production of bioethanol was estimated to be produced at a ratio of 1.015 to ethanol (Jungbluth et al. 2007). The yields of CH_4 from the stillage were assumed to be similar to those from unfermented biomass, although a lower values might be expected.

II.4. Fertiliser credit

The digestate remaining after anaerobic digestion and the stillage following fermentation and distillation (where digestion was not used) were assumed to be used as fertiliser. The fertiliser credit was based upon the amount of nitrogen, phosphorous and potassium in the total dry mass of raw macroalgae (See manuscript Table 1) and the bioavailability. The bioavailability values were taken from a study which investigated the bioavailability of N, P and K in sewage sludge (Warman and Termeer 2005). The values used were 25%, 8% and 50% for N, P and K respectively. The avoided cumulative energy demand and environmental impacts were then calculated as per kg of N, P and K as ammonium sulphate, single superphosphate and potassium chloride respectively.

III. Unit Process Inputs

This section details the inputs to each of the unit processes modelled for each cultivation scenario (S1-S3) and process stream (P1-P3). As the cultivation processes differ between scenarios, these are described separately whereas the processing steps are detailed collectively as they required the same inputs (See manuscript Tables 2 and 3).

III.1. Scenario 1: Bottom planting of G. chilensis

From personal communication with *G. chilensis* farmers, 9 bundles of 200 g (wet weight) of biomass thalli should be planted on each square metre for high productivity of the biomass. The biomass can be planted once and harvested four times before re-planting. Harvesting was assumed to be conducted only once per year. Each hectare therefore requires 18 tonnes of biomass (wet weight) to be recycled and planted every four years corresponding to a recycle rate of 4.5 t/(ha·yr). A shed with lighting was the only input assumed to be required for preparation, the inputs of which were calculated to be 0.67 m^2 of agricultural shed and 5.6 kWh of lighting (see Box 1).

Box 1. Preparation of *G.chilensis* thalli

Shed area

20 m^2 of shed area was assumed sufficient for the preparation of 90,000 bundles (200 g/bundle) of biomass for one hectare of cultivation. The shed was assumed to have a life span of 30 years and was not used for any other processes. Therefore, 0.67 m^2 of shed was used as the shed input modelled as an agricultural shed using Ecoinvent v2.2 (2010).

Lighting

A lighting density of 14 W/m^2 was considered necessary based on the ASHRAE 90[2] energy code for the lighting of office space (Hogan 2004). 10 days were assumed necessary for preparation of one hectare and 8 hours per day of working time. Therefore the energy of the lighting was calculated as:

$$E_{lighting} = 0.014\frac{kW}{m^2}\times 20\ m^2\times 10\ days\times 8\ hours\times 0.25\frac{times}{year} = 5.6\ kWh$$

For the cultivation stage, according to the *G. chilensis* farmers, a diver takes four days to plant one hectare (every four years). The diesel consumption for the vessel used each day was understood to be 30 L or 120 L for the planting of one hectare. The consumption each year for planting one hectare was therefore calculated as 30 L (23.7 kg) of diesel. To calculate the impacts of the diesel consumption by the vessel, the impacts of using the same amount of diesel in the operating barge modelled using data from Ecoinvent v2.2 (2010) were determined. The impacts related to the production of the boat for planting were based on the amortization of a 10 m fishing vessel requiring the production of 0.71 kg of steel and 0.98 kg of aluminium (see Box 2).

Box 2. Cultivation of bottom planted *G. chilensis*

The material requirements for vessel production were based on values from a study investigating the material inputs to a 10 m fishing vessel (Tyedmers 2004). A total steel requirement of 2,260 kg and an aluminium requirement of 3,120 kg were calculated. The material requirements were split at a ratio of 1:8 between the planting and harvesting processes respectively to model the lower usage for planting. Assuming the vessel serviced 20 ha of cultivation area and had a life span of 20 years, the steel consumption was calculated as:

$$M_{steel} = 2260\ kg\times\frac{1}{20}\frac{ha}{ha}\times\frac{1}{20}\frac{y}{y}\times\frac{1}{8}\frac{planting\ time}{harvesting\ time} = 0.71\ kg$$

The aluminium consumption was calculated as:

$$M_{alum} = 3120\ kg\times\frac{1}{20}\frac{ha}{ha}\times\frac{1}{20}\frac{y}{y}\times\frac{1}{8}\frac{planting\ time}{harvesting\ time} = 0.98\ kg$$

The harvesting of the biomass was assumed to be carried out by a fisherman and diver using the same fishing vessel. According to the farmers, the harvesting of one hectare takes three days consuming 90 L of diesel. A total diesel consumption of 90 L (71 kg) was therefore considered as the fuel input, the impacts of which were modelled as for the cultivation. The vessel material amortization was calculated as 4.94 and 6.83 kg/ha of steel and aluminium respectively (see Box. 3).

Box 3. Harvesting of bottom planted *G. chilensis*
The vessel production requirements were calculated as in used in box 2.
Steel consumption was calculated as:

$$M_{steel} = 2260\ kg \times \frac{1}{20}\frac{ha}{ha} \times \frac{1}{20}\frac{y}{y} \times \frac{7}{8}\ \frac{planting\ time}{harvesting\ time} = 4.94\ kg$$

Aluminium consumption was calculated as:

$$M_{alum} = 3120\ kg \times \frac{1}{20}\frac{ha}{ha} \times \frac{1}{20}\frac{y}{y} \times \frac{7}{8}\ \frac{planting\ time}{harvesting\ time} = 6.83\ kg$$

III.2. Scenario 2: Long-line cultivation of G. chilensis

The tying of thalli to rope for long-line cultivation of *G. chilensis* is modelled on the study by Abreu et al. (2009) where 50 g (wet weight) bundles of biomass were attached at 20 cm intervals over the rope length. For each hectare, 1.25 tonnes of biomass was therefore required to be recycled and tied, this amount was subtracted from the total yield of biomass harvested. To allow the tying of thalli an shed input area of 1.33 m^2 requiring 22.4 kWh of lighting was input to the model, the mass of rope was calculated as 111.9 kg of polyamide (see Box 4).

Box 4. Preparation of *G. chilensis* thalli for rope tying
Shed area
40 m^2 of shed area was considered necessary for the preparation of ropes sufficient for each hectare of cultivation area. The shed life span was 30 years, the area modelled was therefore 1.33 m^3.
Lighting
The same lighting density as was used in box 1 was used but it was assumed that 5 days would be sufficient to seed the lines for one hectare. The energy was therefore calculated as:

$$E_{lighting} = 0.014 \frac{kW}{m^2} \times 40\ m^2 \times 5\ days \times 8\ hours = 22.4\ kWh$$

Rope
The rope that the thalli was tied to was assumed to be of 5 mm diameter and made from polyamide. Using data obtained from Lanex a.s. (2013), the density of polyamide rope is 1,140 kg/m^3. The mass input of polyamide rope was therefore calculated as:

$$M_{rope} = 5000\ m \times \pi \times 0.0025^2\ m^2 \times 1140 \frac{kg}{m^3} = 111.9\ kg$$

Once tied, the ropes were required to be deployed offshore as depicted in **Fig. 1** of the manuscript. Structural lines with a diameter of 20 mm perpendicular to the culture lines were assumed at both ends and one at the mid-point, requiring 300 m total length corresponding to an input of 21.5 kg of polyamide. The position of the lines was maintained by using a series of concrete blocks, chains and buoys, corresponding to input values of 952 kg concrete, 38.4 kg steel and 52.5 kg polyethylene respectively. The ropes and buoys were assumed to be deployed using a barge, this was modelled using data from Ecoinvent v2.2 (2010) for the operation of a barge consuming 9.39×10^{-3} kg diesel/t.km. A diesel consumption of 0.045 kg was calculated. The impact of the barge production was included based on a 30 year life span covering 100 ha of cultivation area and split equally between the cultivation and harvesting process. Observation of the culture was assumed to take place once per month over the six month growing period which consumed 0.68 kg diesel and 0.36 kg aluminium to model (see Box 5).

Box 5 Long-line cultivation of *G. chilensis*

The culture ropes were assumed to be attached to stronger 20 mm polyamide ropes, which were placed at each end and the mid-point requiring a total of 300 m of rope. The rope mass was calculated using a density of 1,140 kg/m^3 obtained from Lanex a.s. (2013), the ropes were assumed to have a life span of 5 years. The mass was calculated as:

$$M_{rope} = 300\ m \times \pi \times 0.01^2\ m^2 \times 1140 \frac{kg}{m^3} = 21.5\ kg$$

For anchorage eight concrete blocks of 1 m^3 volume were considered adequate for one hectare. Concrete blocks were assumed to have a life span of 20 years and a density of 2,380 kg/m^3. The mass of concrete was calculated as:

$$M_{concrete} = 8 \times 1\ m^3 \times 2380 \frac{kg}{m^3} \times \frac{1}{20} \frac{y}{y} = 952\ kg$$

Steel chains attached the structural ropes to the concrete blocks, the blocks were assumed to be at a depth of 20 m therefore requiring 160 m of chain. The mass of chain was considered to be 4.8 kg/m (AbosoluteIndustrialLimited 2012) and was assumed to be manufactured from chromium steel with a life span of 20 years. The mass of chain was calculated as:

$$M_{steel} = 160\ m \times 4.8 \frac{kg}{m} \times \frac{1}{20} \frac{y}{y} = 38.4\ kg$$

Buoys were placed at 20 m intervals on each culture line, requiring a total of 250 per hectare. The buoys used were assumed to be the model type "A2 (20"x16")" weighing 2.1kg (BoatFendersDirectLtd 2008+). The buoys were modelled using polyethylene as the material of manufacture and were considered to have a life span of 10 years. The total mass of polyethylene was calculated as:

$$M_{PE} = 250 \times 2.1\ kg \times \frac{1}{10} \frac{y}{y} = 52.5\ kg$$

The distance from the shore to the site was assumed to be 5 km and deploying the ropes required another 5 km. The total mass of rope and buoys was 0.637 t. The diesel consumption of the barge was calculated as:

$$M_{diesel} = 9.39 \times 10^{-3} \frac{kg}{t.km} \times 0.637\ t \times (10\ km + 5\ km) \times 0.5 = 0.045\ kg$$

The cumulative energy demand and environmental impacts of the barge production were included. The barge was assumed to service 100 hectares of cultivation area and have a life span of 30 years. The impacts of production were obtained from the Ecoinvent v2.2 (2010) database and where divided equally between the cultivation and the harvesting processes.

Observation

Observation of the long-line culture was assumed to be conducted using a 25 horsepower fishing vessel modelled on the Alumacraft Escape 145 Tiller (Yamaha Motor Corporation. 2013). The technical specifications suggest a fuel consumption of 10.22 mpg (4.34 km/l) for a velocity of 18.4 mph. Each hectare is visited once a month over a 6 month growing period. For each trip 50 hectares are visited. The fuel consumption to the site was therefore calculated as:

$$M_{diesel} = 10\ km \times \frac{1}{4.34} \frac{l}{km} \times \frac{1}{50} \frac{ha}{ha} \times 6 \frac{times}{year} \times 0.832 \frac{kg}{l} = 0.23\ kg\ diesel$$

The fuel consumption on site was calculated by assuming the vessel travels 500 m around each hectare at 2.6 mph. According to technical specifications the fuel consumption at 2.6 mph is 13 mpg (5.53 km/l). The fuel consumption was therefore calculated as:

$$M_{diesel} = 0.5\ km \times \frac{1}{5.53}\frac{l}{km} \times 6\frac{times}{year} \times 0.832\frac{kg}{l} = 0.45\ kg\ diesel$$

The materials consumption of the vessel was based on the vessel mass specified in the technical data. The total mass was 1,567 lb (711 kg) which was assumed to be aluminium. The total mass input was calculated as:

$$M_{alum} = 711\ kg \times \frac{1}{100}\frac{ha}{ha} \times \frac{1}{20}\frac{y}{y} = 0.36\ kg\ aluminium$$

Harvesting

Harvesting was modelled using the operation of a barge from Ecoinvent v2.2 (2010) which consumes 9.39×10^{-3} kg/t.km. The mass of biomass, ropes and buoys was calculated as 68.2 t. The diesel consumption in the barge was therefore calculated as:

$$M_{diesel} = 9.39 \times 10^{-3}\frac{kg}{t.km} \times 68.2\ t \times (10\ km + 5\ km) \times 0.5 = 4.78\ kg$$

The impacts of the barge production were divided by the 100 ha cultivation area, a life span of 30 years and divide equally between the cultivation and harvesting processes.

Harvesting was assumed to be conducted using the same barge as used for deployment. The distance was the same at 5 km to the cultivation site and 5 km on-site. The biomass yield combined with the mass of ropes and buoys was 68.2 t, corresponding to an input value of 509 t.km or 4.78 kg of diesel consumed by the barge (see Box 5). Half of the barge impacts were allocated to the harvesting process.

III.3. Scenario 3: Long-line cultivation of M. pyrifera

For the production of *M. pyrifera*, a hatchery process was necessary to begin the cultivation of the biomass by inoculating ropes and developing the spores. For spore inoculation, the process begins with stimulating fertile thalli to release spores into a tank containing seawater and rope for cultivation (Gutierrez et al. 2006). This process can be completed in 48 hours and was not included in the model due to its relative insignificance. Prior to transplantation offshore, the spores needed to develop. This step was modelled on the study by Macchiavello et al. (2010) in which the authors developed spores of *M. pyrifera* under laboratory conditions. The inputs to this study were extrapolated for a larger growing area of one hectare (see Box 6). The inputs calculated were 50.4 kg of polyamide rope, 0.25 kg ammonium nitrate, as N, 0.47 kg Sodium phosphate, 971.7 kWh of electricity for water pumping, water treatment, aeration and lighting and 0.67 m^3 of agricultural shed.

Box 6. *M. pyrifera* Hatchery

The hatchery process was modelled on the method used by Macchiavello et al. (2010). In their study, polypropylene rope with a diameter of 3 mm was used for attachment of the spores. A 20 L aquarium was used for spools containing 30 metres of rope. The temperature was maintained at 15°C and two lamps of 40 W were used on a 12:12 hour light period. Aeration was constant for the culture period of 60 days. These values were used but adapted where necessary and extrapolated for a cultivation area of one hectare.

Materials and lighting

This study assumed a two metre distance between rope lines. Therefore, 50 lines of 100 metre length were assumed for one hectare of area requiring 5000m of rope. As the rope needs to be wound around support ropes, a length of 6,250m of rope was used. A density of polyamide rope of 1140 kg/m^3 was obtained from Lanex a.s. (2013). The mass or rope was calculated as:

$$M_{rope} = 6250\ m \times \pi \times 0.0015^2\ m^2 \times 1140\ \frac{kg}{m^3} = 50.4\ kg$$

A tank volume of 4.17 m^3 was assumed necessary to accommodate the rope required for one hectare during spore inoculation. The study by Macchiavello et al. (2010) used two 40 W lamps for 20 L of aquarium, for this study eight 40 W lamps were assumed to be sufficient per cubic metre of tank volume on a 12:12 hour cycle. The energy consumption was therefore calculated as:

$$E = 8\frac{lamps}{m^3} \times 4.17\ m^3 \times 40\ W \times 12\ h \times 60\ days = 960\ kWh$$

Nutrient provision

The medium for spore growth was considered to be Von stosch medium which requires 42.5 mg/L of $NaNO_3$ and 10.75 mg/L of Na_2HPO_4 (Yarish et al. 2012). The concentrations of the other nutrients were considered to be negligible and were ignored. The masses of nutrients required were calculated considering the total water replacement once a week over 60 days which equalled 35.7 m^3. The total N requirement was calculated stoichiometrically as:

$$N = 42.5\frac{g}{m^3} \times 0.165\ \frac{g\ N}{g\ NaNO_3} \times 35.7 m^3 = 0.25\ kg$$

The total mass of Na_2HPO_4 was calculated as:

$$Na_2HPO_4 = 10.75\frac{g}{m^3} \times 35.7 m^3 = 0.38\ kg$$

As data for the CED and environmental impacts of sodium nitrate were not available, the environmental impacts and CED of 0.25 kg (nitrogen) of ammonium nitrate were modelled instead using data from Ecoinvent v2.2 (2010). The total Na_2HPO_4 mass required was modelled as sodium phosphate.

Water pumping

The water for replacing the tank volume was assumed to be pumped from the coast near to the hatchery. The power consumption for water pumping was calculated from the equation for a pump taken from Chadwick et al. (2004):

$$P = 6.89 \times 10^{-6}\ \frac{m^3}{s} \times 1025\frac{kg}{m^3} \times 9.81\frac{m}{s^2} \times 5\ m \times \frac{1}{0.8} = 0.43\ W$$

The water flow is the total volume of water for tank volume replacement over the 60 days which was 35.7 m^3. The total dynamic head was assumed to be 5m as the hatchery was considered to be located beside the coast and frictional head was neglected. The energy consumption over the culture period was therefore 0.62 kWh.

Air pumping

24 hour aeration of the culture tanks was assumed to be conducted using a 0.75 hp sweetwater centrifugal pump (PentairLtd 2013) which was considered sufficient to pump air for each tank developing spores for the total area (100 ha). A horsepower to watt conversion of 745.7 was used which corresponds to a power rating of 0.56 kW or 5.6 W/ha. The pump was operated on a 24 hour basis over the total culture period of 60 days, therefore the energy consumption was calculated as:

$$E_{air} = 0.75\ hp \times 745.7\frac{w}{hp} \times 24\ h \times 60\ d \times \frac{1}{100}\frac{ha}{ha} = 8.05\ kWh$$

Water treatment

The water treatment was modelled on a unit produced by DrydenAqua Ltd with a sub-sand filter and AFM active filter media in a pressure sand filter followed by a 1 micron pleated polyester filter elements to give 1 micron absolute filtration. According to personal correspondence with the manufacturers, the unit has a throughput of 20 m^3/hr and a power rating of approximately 1.5 kW.

The energy consumption was calculated as:

$$E_{WT} = 1.5\ kW \times \frac{35.7}{20} \frac{m^3}{m^3/h} = 2.7\ kWh$$

The water was also assumed to also be treated using UV disinfection based on information from Infralight Pty Ltd. (2013). The unit SF940 has a design flow of 75 L/min and a power rating of 40 W. The energy consumption was calculated as:

$$E_{UV} = 0.04\ kW \times \frac{35.7}{4.5} \frac{m^3}{m^3/h} = 0.32\ kWh$$

Building

The assumed building area required for each hectare of cultivation area was 20 m^2 of shed and the shed was considered to have a life span of 30 years. The area of shed input to the model was therefore 0.67 m^2. The temperature of the building was assumed not to require control however depending upon the location of the hatchery and the time of year this could potentially increase the energy consumption.

Once the spores were developed after 60 days, the lines were assumed to be wound around stronger 10 mm polyamide ropes requiring 110 kg of polyamide rope (see Box 6). The offshore cultivation method of *M. pyrifera* was the same as scenario 2 as depicted in Fig. 2 using the same set-up of concrete blocks, buoys and steel chains. The total mass of ropes and buoys was calculated as 1,023 kg which was assumed to be transported by barge consuming 0.072 kg of diesel. The impact of the barge fabrication was included using the same method as scenario 2. Observation was conducted once a month, in this case over a nine month growth period consuming 1.02 kg diesel and 0.36 kg aluminium (see Box 7). The concrete, steel and polyethylene material inputs were the same as for scenario 2.

Harvesting was modelled using the barge that was used for deployment. The mass of biomass produced as well as the ropes and buoys was calculated as 118.5 t, corresponding to a diesel consumption of 8.35 kg (see Box 7). The impacts of the barge production were divided equally between the harvesting and cultivation processes.

Box 7. Cultivation of M. pyrifera

Support ropes

The culture ropes were assumed to be wound around stronger 10 mm polyamide ropes. A total length of 5,000 m of support rope was necessary. 3 lengths of 100 m of additional structural rope with a diameter of 20 mm was assumed to be used for attachment of the support ropes and culture ropes. The rope mass was calculated using a density of 1,140 kg/m3 obtained from Lanex a.s. (2013), the ropes were assumed to have a life span of 5 years. The mass was calculated as:

$$M_{rope} = \left(5000\ m \times \pi \times 0.005^2\ m^2 + 300\ m \times \pi \times 0.01^2\ m^2\right) \times 1140 \frac{kg}{m^3} \times \frac{1}{5} \frac{y}{y} = 111.0\ kg$$

The mass of structural ropes, buoys, steel chains and concrete blocks were the same as detailed in box 5 for the long-line cultivation of *G.chilensis*.

Deployment

$$M_{diesel} = 9.39\times10^{-3}\,\frac{kg}{t.km}\times1.023\ t\times(10\ km + 5\ km)\times0.5 = 0.072kg$$

Observation
Using the same vessel and assumptions as box 5, the diesel consumption was calculated as:

$$M_{diesel} = 10km\times\frac{1}{4.34}\frac{l}{km}\times\frac{1}{50}\frac{ha}{ha}\times9\frac{times}{year}\times0.832\frac{kg}{l} = 0.34\ kg\ diesel$$

The fuel consumption on site was calculated by assuming the vessel travels 500 m around each hectare at 2.6 mph. According to technical specifications the fuel consumption at 2.6 mph is 13 mpg (5.53 km/l). The fuel consumption was therefore calculated as:

$$M_{diesel} = 0.5km\times\frac{1}{5.53}\frac{l}{km}\times9\frac{times}{year}0.832\frac{kg}{l} = 0.68\ kg\ diesel$$

The vessel production was assumed to be the same as box 5 requiring 0.36 kg aluminium.
Harvesting
The total mass of biomass, ropes and buoys to be harvested was calculated to be 118.5 t, based on the diesel consumption of the barge the mass of diesel consumed was calculated as:

$$M_{diesel} = 9.39\times10^{-3}\,\frac{kg}{t.km}\times118.5\ t\times(10\ km + 5\ km)\times0.5 = 8.35kg$$

III.4. Pre-processing

The pre-processing method was the same for each scenario. Prior to processing, the biomass was transported from the boat landing point to the processing facilities and then ground. The facilities were assumed to be 100 m from the point where the boat landing point was located. The method of transport was a 100 m long conveyor belt with a power rating of 0.68 kW, the electricity consumption depended upon the yield of biomass being transported (Box 8). The conveyor belt transported the biomass to a wet grinding attritor, with a power rating of 93.2 kW. The calculations for energy consumption depended upon the biomass throughput and material allocation depended upon cultivation area. (see Box 9).

Box 8. Conveyor belt design

A conveyor belt was assumed to transport the harvested biomass from the point where the boats land to the processing units. This distance was considered to be 100 m. The conveyor belt was designed using data from Rulli Rulmeca SpA. (2010). A belt with width 500 mm was chosen and angle of surcharge 5° on a flat roller set. The fixed coefficient of resistance was 2.1, the passive coefficient of resistance, 1, the coefficient of friction for internal rotating parts, 0.016, the belt weight per linear meter, 3.45 kg/m, the weight of lower rotating parts, 1.2 kg/m, the weight of upper rotating parts, 3.09 kg/m, weight of conveyed material, 3.5 kg/m and the height change, 3m.
The tangential force was calculated as:

$$F_u = \left(100m\times2.1\times0.016\times\left(2\times3.45\frac{kg}{m} + 3.5\frac{kg}{m} + 1.2\frac{kg}{m} + 3.09\frac{kg}{m}\right) + \left(3.5\frac{kg}{m}\times3m\right)\right)\times0.981 = 58.8\ \mathrm{N}$$

The belt velocity was assumed to be 1 m/s and an efficiency of reduction gear of 0.86. The belt driving power was calculated as:

$$P = \frac{58.8\ N \times 1\frac{m}{s}}{100 \times 0.86} = 0.68\ kW$$

The energy consumption of the conveyor belt was calculated by multiplying the time taken to transport the biomass by the driving power of the conveyor belt. The time taken was calculated by dividing the volume of biomass harvested by the load volume which for the size of the belt was 12.6 m^3/h.

The material consumption was calculated as the mass of steel of the upper rotating parts (3.09 kg/m) and the lower rotating parts (1.2 kg/m) and the mass of rubber (3.45 kg/m). The steel parts were assumed to have a life span of 10 years and the rubber belt a life span of 5 years.

Scenario 1 (Bottom cultivated *G. chilensis*)

Energy consumption:

$$E = 0.68\ kW \times \frac{1}{12.5}\ \frac{h}{m^3} \times 101.5\ m^3 = 5.5\ kWh$$

Material consumption:

$$M_{steel} = \left(3.09\frac{kg}{m} + 1.2\frac{kg}{m}\right) \times 100\ m \times \frac{1}{20}\frac{ha}{ha} \times \frac{1}{10}\frac{y}{y} = 2.16\ kg$$

$$M_{rubber} = \left(3.45\frac{kg}{m}\right) \times 100\ m \times \frac{1}{20}\frac{ha}{ha} \times \frac{1}{5}\frac{y}{y} = 3.45\ kg$$

Scenario 2 (Long line cultivated *G. chilensis*)

Energy consumption:

$$E = 0.68\ kW \times \frac{1}{12.5}\ \frac{h}{m^3} \times 66.0\ m^3 = 3.58\ kWh$$

Material consumption:

$$M_{steel} = \left(3.09\frac{kg}{m} + 1.2\frac{kg}{m}\right) \times 100\ m \times \frac{1}{100}\frac{ha}{ha} \times \frac{1}{10}\frac{y}{y} = 0.43\ kg$$

$$M_{rubber} = \left(3.45\frac{kg}{m}\right) \times 100\ m \times \frac{1}{100}\frac{ha}{ha} \times \frac{1}{5}\frac{y}{y} = 0.69\ kg$$

Scenario 3 (Long line cultivated *M. pyrifera*)

Energy consumption:

$$E = 0.68\ kW \times \frac{1}{12.5}\ \frac{h}{m^3} \times 117.5\ m^3 = 6.38\ kWh$$

Material consumption:

$$M_{steel} = \left(3.09\frac{kg}{m} + 1.2\frac{kg}{m}\right) \times 100\ m \times \frac{1}{100}\frac{ha}{ha} \times \frac{1}{10}\frac{y}{y} = 0.43\ kg$$

$$M_{rubber} = \left(3.45\frac{kg}{m}\right) \times 100\ m \times \frac{1}{100}\frac{ha}{ha} \times \frac{1}{5}\frac{y}{y} = 0.69\ kg$$

Box 9 Grinding attritor

The grinding attritor is based on the Q-100 unit produced by Union process. (2013). The unit has a throughput of 130 gallons per minute (32.7 t/h), an average power requirement of 125 horsepower (93.2 kW) and a weight of 9,900 pounds (4,491 kg). The attritor was assumed to be produced from chromium steel and have a life span of 10 years.

Scenario 1 (Bottom cultivated *G. chilensis*)

Energy consumption:

$$E = 93.2\ kW \times \frac{1}{32.7}\frac{h}{t} \times 101.5\ t = 289.3\ kWh$$

Material consumption:

$$M_{steel} = 4491\ kg \times \frac{1}{20}\frac{ha}{ha} \times \frac{1}{10}\frac{y}{y} = 22.5\ kg$$

Scenario 2 (Long line cultivated *G. chilensis*)
Energy consumption:

$$E = 93.2\ kW \times \frac{1}{32.7}\frac{h}{t} \times 66.0\ t = 188.0\ kWh$$

Material consumption:

$$M_{steel} = 4491\ kg \times \frac{1}{100}\frac{ha}{ha} \times \frac{1}{10}\frac{y}{y} = 4.49\ kg$$

Scenario 3 (Long line cultivated *M. pyrifera*)
Energy consumption:

$$E = 93.2\ kW \times \frac{1}{32.7}\frac{h}{t} \times 117.5\ t = 334.9\ kWh$$

Material consumption:

$$M_{steel} = 4491\ kg \times \frac{1}{100}\frac{ha}{ha} \times \frac{1}{10}\frac{y}{y} = 4.49\ kg$$

III.5. Processing

Two processing methods were modelled in the LCA study, fermentation/distillation to bioethanol and anaerobic digestion to biogas. No studies have been conducted investigating the energy use or environmental impacts of energy recovery from macroalgal biomass on a large scale, therefore for fermentation/distillation the model relied upon Ecoinvent data (Jungbluth et al. 2007) for first generation biomass and the anaerobic digestion of the biomass was modelled using data for sludge digestion (Tchobanoglous et al. 2003).

Fermentation and distillation are the processing methods of converting organic material to ethanol through biological and thermal processes. Bioethanol fuel requires a purity of 99.7% and can be mixed with fossil fuels up to a proportion of 85% in specialised engines (Luo et al. 2009). The cumulative energy demand and impacts were calculated using data from the Ecoinvent v2.2 (2010) database for the electricity, heat and material consumption required to produce 99.7% bioethanol from corn feedstock. The material and energy inputs were adjusted to the macroalgae as a feedstock based on the carbon content ratio of the corn and the algae (see box 10). As the moisture content of the macroalgae was much higher, the contribution of plant use was based on the fresh mass of biomass into the fermentation/distillation plant.

Box 10. Fermentation and distillation of biomass

Fermentation and distillation was based on the production of bioethanol from corn modelled by Ecoinvent (Jungbluth et al. 2007). The inputs to the fermentation and distillation process used by

Ecoinvent for producing 1kg of bioethanol (95%) are displayed in Table B. The values of electricity and heat include the input for pretreatment, saccharification, fermentation and distillation but not for stillage treatment.

Table A. Inputs to the production of 1 kg of bioethanol (95%) from corn.

Input	**Unit**	**Value**
Corn	kg	3.226
Electricity	kWh	0.134
Heat	MJ	3.631
Ammonium sulphate	kg, as N	9.655×10^{-3}
Diammonium phosphate	kg, as N	9.655×10^{-3}
Soda powder	kg	3.607×10^{-2}
Sulphuric acid	kg	2.404×10^{-2}
Ethanol fermentation plant		2.525×10^{-10}

The inputs to the study were modified by adjusting the values to the equivalent carbon content of the macroalgae. According to Ecoinvent (Jungbluth et al. 2007), the carbon content of the corn grains are 0.375 kg per kg of fresh mass (37.5%). The carbon content of both macroalgae species was assumed to be 30% of the dry mass or 4.5% of the fresh mass, therefore each input was multiplied by:

$$Conversion\ factor = \frac{0.045}{0.375 \times 3.226} \frac{1}{kg} \times mass\ of fresh\ biomass\ kg$$

The fraction of the ethanol fermentation plant was calculated by considering the mass of biomass into the plant. The contribution of the plant for 3.226 kg of corn was multiplied by the mass of macroalgae biomass (w.w) and divided by 3.226.

Upgrading bioethanol to 99.7%

The process of upgrading the bioethanol from 95% to 99.7% was modelled on information from Ecoinvent (Jungbluth et al. 2007), the inputs are displayed in Table C for 1 kg of bioethanol 99.7%. The total input for upgrading was calculated by multiplying the input values by the total ethanol produced in each scenario.

Table B. Inputs required for upgrading bioethanol from 95% to 99.7%.

Input	Unit	Value
Corn	kg	3.226
Electricity	kWh	0.134
Heat	MJ	3.631
Ammonium sulphate	kg, as N	9.655×10^{-3}
Diammonium phosphate	kg, as N	9.655×10^{-3}
Soda powder	kg	3.607×10^{-2}
Sulphuric acid	kg	2.404×10^{-2}
Ethanol fermentation plant		2.525×10^{-10}

Table C. Inputs for each scenario for the fermentation and distillation process.

Input	Unit	Scenario 1	Scenario 2	Scenario 3
Mass of fresh biomass	t	101.5	66.0	117.5
Electricity	kWh	507.2	329.6	587.2
Heat	MJ	13,707.2	8,906.3	15,868.0
Ammonium sulphate	kg, as N	36.5	23.7	42.2
Diammonium phosphate	kg, as N	36.5	23.7	42.2
Soda powder	kg	136.2	88.5	157.6
Sulphuric acid	kg	90.8	59.0	105.1
Ethanol fermentation plant		7.946×10^{-6}	5.163×10^{-6}	9.198×10^{-6}
Electricity (upgrading)	kWh	7.9	5.1	18.8
Heat (upgrading)	MJ	894.8	581.4	2,131.5
Ethanol fermentation plant (upgrading)		4.72×10^{-8}	3.07×10^{-8}	1.12×10^{-7}

Alternative data tested for fermentation and distillation

Input data for fermentation and distillation were also tested using data that were used in an alternative LCA study (Alvarado-Morales et al. 2013) which based data on an experimental study (Luo et al. 2010). The inputs per MJ of bioethanol are displayed in Table E.

Table D. Alternative inputs for fermentation/distillation of microalgae per MJ of bioethanol.

Process	Energy consumption (MJ/MJ_{ETOH})
Fermentation	0.056
Vapour compression steam stripping (Heat)	0.161
Molecular sieve (Heat)	0.056
Vapour compression steam stripping (Electricity)	0.051
Vapour compression distillation (Electricity)	0.067

The energy consumption values were multiplied by the lower heating value of the bioethanol produced.

The study from which the data were taken (Alvarado-Morales et al. 2013) does not include the fermentation/distillation infrastructure however for consistency this study included the ethanol fermentation plant modelled using data from Ecoinvent (Jungbluth et al. 2007). The contribution of the plant was calculated using the same methodology based on the ratio of carbon content of the macroalgae to corn.

Anaerobic digestion is the process which facilitates the production of biogas through the bacterial transformation of biomass. The process requires an anaerobic tank to contain the biomass and a method of sludge heating and mixing. The temperature of the tank depends upon the desired conditions, this study considered the use of mesophilic conditions, a temperature of 37°C was assumed.

The input data related to electricity, heat and material consumption were calculated using information and data from the design of anaerobic digestion systems for digestion of sludge in wastewater treatment plants (Tchobanoglous et al. 2003). The design was based on a simple mechanical mixing tank constructed of concrete which was assumed to operate at 37°C with a retention time of 38 days. The calculations for the energy and material requirements for each process stream can be viewed in Box 11.

Box 11. Anaerobic digestion of biomass

Anaerobic digestion of the macroalgae was modelled based on data and information for sludge digestion (Tchobanoglous et al. 2003). The mixing power of the digester is dependent upon the volume of the digester. According to Metcalf and Eddy (Tchobanoglous et al. 2003), the power requirement for mixing 1 m^3 of digester volume is between 0.005 and 0.008 kW. An average value of 0.0065 kW/m^3 was used in this study. The digester volume necessary to accommodate one hectare's yield of biomass was calculated by multiplying the influent volume of biomass by the retention time (38 days). The density of the algal sludge was taken to be 1,000 kg/m^3. The mixing energy was calculated as:

$$E_{mixing} = 0.0065 \frac{kW}{m^3} \times Biomass\ volume\ m^3 \times 38\ d \times 24\ h$$

The anaerobic digestion was assumed to operate at a temperature of 37°C, the biomass sludge entering the digester therefore had to be heated. The energy required to heat the sludge was calculated based on the mass of incoming sludge and the temperature difference between the digester and the sludge. The heat capacity was assumed to be the same as water (4.2 J/kg.°C) and the environmental temperature was assumed to be 20°C. The calculation was therefore:

$$E_{heating} = influent\ mass\ kg \times (37℃ - 20℃) \times 4200 \frac{J}{kg.℃} \times \frac{1}{3600}$$

The heat required to account for heating loss in the digester was calculated based on heat transfer coefficients from Metcalf and Eddy (Tchobanoglous et al. 2003), for plain concrete walls above ground with insulation (0.7 $W/m^2.°C$), a plain concrete floor with dry earth (1.7 $W/m^2.°C$) and a 100 mm thick, covered and insulated concrete fixed cover (1.4 $W/m^2.°C$). The areas of the floor, cover and walls were determined by the volume of biomass sludge. For each hectare the digester was assumed to be cylindrical with a diameter of 6m and a corresponding floor and ceiling area of 28.3 m^2. The wall areas were calculated by dividing the volume of influent biomass by the floor area. The heat energy required for the heat loss was therefore calculated as:

$$E_{h\ loss} = (A_{wall}\ m^2 \times 0.7 \frac{W}{m^2.℃} + A_{base}\ m^2 \times (1.7 + 1.4) \frac{W}{m^2.℃}) \times (37℃ - 20℃) \times 24\ h \times 38\ d$$

The impacts related to the infrastructure for anaerobic digestion were calculated based on the area and depth of the walls, roof and floors. The walls and floors were assumed to be 300 mm thick concrete and the cover from 100 mm concrete. The impacts were calculated using data from Ecoinvent v2.2 (2010) for concrete with a density of 2,380 kg/m^3 and were divided by the life span of the digester (30 years).

Table E. Anaerobic digestion process inputs for each scenario for process steam, P2.

Input	Unit	Scenario 1	Scenario 2	Scenario 3
Mass of fresh biomass	T	101.5	66.0	117.5
Electricity (mixing)	kWh	601.7	391.0	696.5
Heat (heating)	MJ	14,783.0	11,318.8	16,342.2
Concrete	kg	2,776.6	2,184.4	3,043.2

Table F. Anaerobic digestion process inputs for each scenario for process stream, P3.

Input	Unit	Scenario 1	Scenario 2	Scenario 3
Mass of fresh biomass	T	89.5	58.2	89.0
Electricity (mixing)	kWh	530.8	344.9	527.6
Heat (heating)	MJ	13,617.1	10,561.2	13,564.7
Concrete	kg	2,577.3	2,054.9	2,568.4

Supplementary data B –Modelling of the Chilean national grid

The electricity supply from the national grid in Chile was modelled using information from a study produced for the Global Energy Network Institute (Woodhouse 2011). The contributions of different sources to the national grid are detailed in table A below alongside the data that were used for the model. All data for modelling of the national grid were taken from Ecoinvent v2.2 (2010).

Table G. Contribution of each source of electricity to the Chilean national grid and the source of data for the LCA model

Source	**(%)**	**Data used**	**Location**
Natural gas	36	Electricity, Industrial gas, at power plant	UCTE
Coal	17	Electricity, hard coal, at power plant	US
Diesel (Modelled as oil)	7	Electricity, oil, at power plant	UCTE
Hydroelectricity (reservoir)	27	Electricity, hydropower, at reservoir power plant, non alpine regions	RER
Hydroelectricity (run-of-river)	11	Electricity, hydropower, at run-of-river power plant	RER
Wood	2	Electricity, at cogen 6400kWth, wood, allocation energy	CH
Wind	0.1	Electricity, at wind power plant	RER

Note: UCTE - Union for the coordination of transmission of electricity (Europe); RER - Europe; CH - Switzerland

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