Energy Input, Carbon Intensity, and Cost for Ethanol Produced from Brown Seaweed

by

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B.Eng, University of Victoria, 2010

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Supervisory committee

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Brown macroalgae or brown seaweed is a promising source of ethanol that may avoid the challenges of arable land use, water use, lignin content, and the food vs. fuel debate associated with first generation and cellulosic ethanol sources; however, this promise is challenged by seaweed's high water content, high ash content, and natural composition fluctuations. Notably, lifecycle studies of seaweed ethanol are lacking in the literature. To address this gap, a well-to-wheel model of ethanol production from farmed brown seaweed was constructed and applied to the case of *Saccharina latissima* farming in British Columbia (BC), Canada, to determine energy return on energy invested (EROI), carbon intensity (CI), and near shore seaweed farming production potential for seaweed ethanol and to examine the production cost of seaweed ethanol. Seaweed farming and ethanol production were modeled based on current BC farming methods and the dry grind corn ethanol production process; animal feed was included as an ethanol co-product, and co-product credits were considered. A seaweed ethanol yield calculation tool that accounts for seaweed composition was proposed, and a sensitivity study was done to examine case study data assumptions.

In the case study, seaweed ethanol had lower CI than sugarcane, wheat, and corn ethanol at 10.1 gCO_2e/MJ, and it had an EROI comparable to corn ethanol at 1.78. Seaweed ethanol was potentially profitable due to significant revenue from animal feed sales; however, the market for seaweed animal feed was limited by the feed's high sodium content. Near shore seaweed farming could meet the current demand for ethanol in BC, but world near shore ethanol potential is likely

an order of magnitude lower than world ethanol production and two orders of magnitude lower than world gasoline production. Composition variation and a limited harvest season make solar thermal or geothermal seaweed drying and storage necessary for ethanol production in BC. Varying seaweed composition, solar thermal drying performance, co-product credits, the type of animal feed produced, transport distances, and seaweed farming performance in the sensitivity study gave an EROI of over 200 and a CI of -42 gCO_2e/MJ in the best case and an EROI of 0.64 and CI of 33 gCO_2e/MJ in the worst case. Co-product credits and the type of animal feed produced had the most significant effect overall, and the worst cases of seaweed composition and solar thermal seaweed drying system performance resulted in EROI of 0.64 and 1.0 respectively.

Brown seaweed is concluded to be a potentially profitable source of ethanol with climate benefits that surpass current ethanol sources; however, additional research into seaweed animal feed value, co-product credits, large scale seaweed conversion, and the feasibility of solar thermal or geothermal seaweed drying is required to confirm this conclusion.

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Nomenclature

Acronyms

BC	British Columbia
CAD	Canadian dollars
CI	Carbon intensity
COP	Coefficient of performance
$DDGS$	Dry distiller's grains with solubles
$EROI$	Energy return on energy invested
$G3P$	Glyceraldehyde-3-phosphate
$gCO2e$	GHG emission in grams of carbon dioxide equivalent
GHG	Greenhouse gas
GWP	Global warming potential
HHV	Higher heating value
$MDGS$	Modified distiller's grains with solubles
USD	US dollars
$WDGS$	Wet distillers grains with solubles

Symbols

A	Fraction of total dry grind electricity consumption used for feed processing
B	Seaweed bulk density ($kg \cdot m^{-1}$)
C_{CAP}	Ethanol plant capital cost (\$)
C_{DD}	Maximum drying and delivery cost ($\$ \cdot tonne^{-1}$)
C_F	Annual feedstock cost ($\$ \cdot yr^{-1}$)
C_{FSW}	Fresh seaweed production cost ($\$ \cdot tonne^{-1}$)
CI	Carbon intensity for energy carrier produced ($gCO_2e \cdot MJ^{-1}$)
C_{OP}	Ethanol plant annual operating cost less annual feedstock cost ($\$ \cdot yr^{-1}$)
COP_H	Solar thermal system COP
C_{Sl}	Silo capital cost ($\$ \cdot m^{-3}$)
C_{SW}	Maximum feedstock cost ($\$ \cdot tonne^{-1}$)
D'	Total specific co-product production ($kg \cdot MJ^{-1}$)
D'_F	Specific mass of co-product similar to animal feed ($kg \cdot MJ^{-1}$)
D'_R	Specific mass of co-product similar to mineral supplements ($kg \cdot MJ^{-1}$)

D_{corn}	Dry grind animal feed production rate ($kg \cdot L^{-1}$)
D_i'	Specific mass of co-product i produced ($kg \cdot MJ^{-1}$)
E'	Specific energy input ($MJ \cdot MJ^{-1}$)
$E_{CE,i}$	Electricity input for producing co-product i ($MJ \cdot MJ^{-1}$)
$E_{CF,i}$	Fuel input for producing co-product i ($MJ \cdot MJ^{-1}$)
$E_{EE,C}$	Electricity consumption in dry grind corn ethanol production ($MJ \cdot L^{-1}$)
$E_{EF,C}$	Natural gas consumption in dry grind corn ethanol production ($MJ \cdot L^{-1}$)
E_{input}	Total energy input for carrier production (MJ)
E_{out}	Total energy carrier output (MJ)
$EROI$	Energy return on energy invested
F	Fuel use ($MJ \cdot tonne^{-1} km^{-1}$)
F_{SC}	Skiff fuel use at cruising speed ($L \cdot km^{-1}$)
F_{SI}	Skiff fuel use at idle ($L \cdot hr^{-1}$)
G'	Specific direct GHG emission ($gCO_2e \cdot MJ^{-1}$)
G_I'	Specific indirect GHG emission ($gCO_2e \cdot MJ^{-1}$)
GWP_{EtOH}	Ethanol 100 year GWP ($gCO_2e \cdot g^{-1}$)
G_{out}	Total GHG emission for carrier production ($gCO_2e \cdot MJ^{-1}$)
H	Seaweed water removal heat requirement ($MJ \cdot kg^{-1}$)
HHV	Higher heating value ($MJ \cdot kg^{-1}$)
HHV_V	Higher heating value, per unit volume ($MJ \cdot L^{-1}$)
I	Carbon intensity for energy consumed ($gCO_2e \cdot MJ^{-1}$)
$K_{M,i}$	GHG emission credit for co-product i ($gCO_2e \cdot kg^{-1}$)
K_M'	Total specific GHG emission co-product credit ($gCO_2e \cdot MJ^{-1}$)
$K_{N,i}$	Energy credit for co-product i ($MJ \cdot kg^{-1}$)
K_N'	Total specific energy co-product credit ($MJ \cdot MJ^{-1}$)
$L_{CL,i}$	Coastline length in region i (km)
L_T	Horizontal rope seeded per sporeling batch ($m \cdot batch^{-1}$)
M_d	Dry seaweed moisture content
M_f	Fresh seaweed moisture content
N_F	Inflation correction factor (2012 $USD \cdot 1999\ USD^{-1}$)
O	Operating cost ($\$ \cdot yr^{-1}$)
P	Annual seaweed production ($tonne \cdot yr^{-1}$)
P_T	Sporeling tank electrical power draw (W)

P_{cap}	Ethanol plant production capacity ($L \cdot yr^{-1}$)
R	Ethanol plant annual ethanol and co-product revenue ($\$ \cdot yr^{-1}$)
R_C	Seaweed to ethanol conversion rate ($kg \cdot kg^{-1}$)
R_{EX}	2012 CAD/US exchange rate ($CAD \cdot USD^{-1}$)
R_P	Horizontal rope seaweed production rate ($kg \cdot m^{-1}$)
R_{SW}	Rate of fresh seaweed production ($kg \cdot batch^{-1}$)
S	Capital cost ($)
T	Fuel use per unit of fresh seaweed produced ($MJ \cdot kg^{-1}$)
W_{EtOH}	Wholesale ethanol price ($\$ \cdot L^{-1}$)
W_{GR}	Wholesale seaweed feed price ($\$ \cdot tonne^{-1}$)
X_{E10}	Gasoline to ethanol blend equivalence ($L \cdot L^{-1}$)
Y_x	Near shore ethanol yield for coastline section x ($L \cdot yr^{-1}$)
d	Transport distance (km)
f_i	Mass fraction of total seaweed solids for seaweed component i
$f_{C,i}$	Mass fraction of co-product i produced
i_{ROR}	Rate of return
m'	Specific mass flow ($kg \cdot MJ^{-1}$)
m_{EL}	Ethanol vapor loss in distribution ($kg \cdot kg^{-1}$)
m_{FR}	Mass of fertilizer applied per unit fresh seaweed produced ($kg \cdot kg^{-1}$)
m_{SW}	Mass of fresh seaweed (kg)
n_B	Sporeling batches produced per number of frond collection trip (batch)
n_{G+I}	Number of return trips for gathering mature fronds and installing seedlings per unit of horizontal rope (m^{-1})
t_C	Sporeling batch culture time ($weeks \cdot batch^{-1}$)
t_{FC}	Spore bearing frond collection time ($min \cdot batch^{-1}$)
t_{HARV}	Horizontal rope harvesting time ($min \cdot m^{-1}$)
t_{IDL}	Total skiff idling time ($min \cdot m^{-1}$)
t_{INST}	Sporeling twine installation time ($min \cdot m^{-1}$)
t_{OL}	Ethanol plant operating life (yr)
t_{WD}	Sporeling installation work day (hr)

Greek

δ_{AF}	Animal feed production capital cost scaling factor
δ_{EF}	Ethanol production fuel scaling factor
δ_{EI}	Energy input cost scaling factor
η_i	Conversion efficiency for seaweed component i
μ	Ethanol energy equivalent for fresh seaweed
ρ_{EtOH}	Ethanol density
ψ_i	Ideal ethanol yield for seaweed component i

Superscripts

$'$	Specific quantity. Indicates quantities that are expressed per MJ of ethanol higher heating value delivered to vehicle fuel tank.

Subscripts

AC	Air compressor
AF	Animal feed production
BC	British Columbia
BF	Sporeling boat fuel
BR	Barge
C	Coal
CH	China
D	Typical dry grind animal feed
DE	Drying system electricity
DF	Dry feed
Dn	Denaturant
Ds	Distillation
EE	Ethanol production electricity
EF	Ethanol production fuel
EI	Ethanol plant energy input
$ELEC$	Electricity
$EtOH$	Ethanol
F	Animal feed displacement

Fr	Fermentation capital cost
G	Gasoline
IDL	idling during production operations
LSO	Labor, supplies, and overhead
M	Mineral supplement displacement
MF	Modified feed
NG	Natural gas
PE	Process electricity
PF	Process fuel
RM	Raw materials
SC	Skiff at cruising speed, partial load
SE	Sporeling electricity
SF	Sporeling heating fuel
SI	Skiff at idle
SK	Skiff under full load
SLO	Storage and load out system
SO	Support operations
St	Dry seaweed storage system
ST	Solar thermal system input
TF	Transport fuel
TK	Fuel truck
TN	Train
TR	Transport of mature seaweed, fronds, and sporelings
W	World coastline
WF	Wet feed
WT	Wastewater treatment capital cost
X	Coastline in region of interest

1 Background and motivation

1.1 Ethanol to combat climate change

Transportation accounts for 13% of total anthropogenic GHG emissions with 95% coming from the use of petroleum derived diesel and gasoline [1]. Because of its relative compatibility with existing infrastructure, bioethanol can be used as a near term replacement for gasoline that offers a mechanism to reduce transportation emissions; however, replacement of gasoline with ethanol is limited by the quantity of bioethanol that can currently be produced.

Currently, the majority of bioethanol is produced from ether corn or sugarcane. Known as first generation ethanol sources, both corn and sugarcane face barriers that limit their production. Corn production requires arable land, irrigation, and fertilizer, and corn ethanol production has a potentially negative effect on corn production for human consumption, driving the "food vs. fuel" debate [2]. Sugarcane does not compete with food production like corn; however, expanded sugarcane production can contribute to deforestation and wetland destruction [3], and sugarcane production is limited to specific climates. Cellulosic biomass has been proposed as a solution to the problems of first generation ethanol sources as it is ubiquitous in the biosphere, it can be grown in almost any climate, and it typically does not require arable land, irrigation, or fertilizer. However, cellulosic biomass is difficult to convert to ethanol due to the presence of lignin and cellulose's natural resistance to hydrolysis.

1.2 Seaweed as an ethanol source

Macroalgae is a promising source of ethanol that may avoid the challenges of first generation and cellulosic ethanol sources. Commonly called seaweed, it is free of the food vs. fuel debate, needs no arable land or fresh water, and lacks lignin [4]; however, it has high water content (75-90%), high ash content (22-37%) [5], and it experiences significant monthly fluctuations in fermentable sugar content [6]. Seaweed ethanol has received significant attention in the literature, but the effect of water content, ash content, and composition variation on the overall ethanol production system has not been fully addressed.

Roesijadi et al. [7], Bruton et al. [5], Reith et al [8], Horn [9], and Hennenberg et al. [10], provide an excellent review of current research on seaweed in general, seaweed bioenergy production, and co-product production.

Brown seaweeds are considered the most likely candidates for energy production, and the brown seaweed *Saccharina japonica* is the most farmed seaweed by mass, accounting for 33% of global near shore seaweed production [7]. Apart from water, ash, and a small quantity of miscellaneous metabolites, brown seaweeds contain seven energy rich biomolecules: laminarin, mannitol, alginate, protein, cellulose, fucans, and small quantities of lipids [11]. Of these components, laminarin and mannitol are considered easily fermentable [9], and recent work has shown that alginate fermentation is possible with genetically modified fermenting organisms [4][12].

For co-product production, pigment proteins, cellulose, fucans, and metabolite derived phenolic compounds can be extracted from seaweed and sold to limited markets [7], or the whole seaweed mass can be anaerobically digested into methane [13], converted into fertilizer, or potentially made into animal feed. Seaweed fertilizer can act as biostimulant [5], and seaweed ash contains high amounts of beneficial minerals and trace elements [14] [15] which may increase its value as animal feed. Feed production is simpler than extraction or digestion, requiring only dewatering and or drying of whole seaweed, and animal feed is the dominant co-product in the corn ethanol industry. Replacing conventional animal feed with co-product animal feed from corn ethanol results in a significant reduction in both *greenhouse gas* (GHG) emissions and energy use in the livestock industry, which is accounted to ethanol producers as *co-product credits* [16]. Animal feed production and co-product credits have not been considered for seaweed ethanol systems.

Conversion of seaweed to ethanol has been achieved at lab scale [4] [9][12], and two studies of bio-ethanol production from seaweed were reviewed by Roesijadi et al. [7]. In the first study, Aizawa et al. [17] examined ethanol production from seaweed farmed in both coastal and offshore zones, and estimated resource consumption for cultivation and production. The overall energy balance was considered similar to that of corn ethanol. Peter et al. [18] examined seaweed production with juvenile seaweed cultured at a fish hatchery then transferred to ocean farm structures for a final grow out. Pumping in the culturing stage, boat fuel for maintenance during the growth phase, and ethanol distillation were identified as the largest energy consumers, but no numerical results were given. Roesijadi et al. concluded that lifecycle analyses for seaweed biofuel are scarce in the literature, and that additional assessment is necessary to provide an adequate comparison between seaweed biofuels and conventional biofuels. The effect of seaweed composition variation and of co-product credits have not been considered, lifecycle GHG emissions and energy input have not been quantified, and the potential global impact of seaweed ethanol has not yet been examined.

1.3 Objective

The objective of this thesis is twofold: 1) develop a general well-to-wheel model of seaweed ethanol production to work towards a comprehensive lifecycle analysis of seaweed ethanol. 2) Apply the general model to the case of ethanol production from farmed *Saccharina latissima* in British Columbia (BC) to determine the effect of high water content, high ash content, and composition variation on ethanol performance. Both the general model and case study examine the energy inputs and GHG emissions associated with seaweed ethanol production, both include an estimate of ethanol production potential based on near shore seaweed farming, and both address the cost of seaweed ethanol production. The case study also includes a sensitivity study to determine how ethanol performance is affected by assumed input data.

1.4 Outline

The thesis body is divided into seven chapters. Chapter 2 provides background information on seaweed reproduction, composition variation, and farming practices. Chapter 3 provides background information on the ethanol production process and the effect of feedstock harvest season on the overall production system, and both dry grind corn ethanol production and seaweed ethanol production are discussed. Chapter 4 describes the well-to-wheel model of brown seaweed ethanol production including system boundaries and the specific inputs and outputs considered, and it proposes a tool for estimating ethanol yield from any brown seaweed based on seaweed composition. Chapter 5 outlines the case study of seaweed ethanol production in BC, defining the location specific parameters required by the model and outlining a sensitivity study on case study input data. Chapter 6 presents results from the case study and the sensitivity study, Chapter 7 gives a discussion of the results, and Chapter 8 gives conclusions from the case study and recommendations for future work.

2 Background on seaweed

This chapter discusses background information on seaweed covering the two basic forms of seaweed reproduction, the factors that influence seaweed composition, and seaweed farming techniques. Both seaweed reproduction and seaweed farming techniques affect the inputs required to produce seaweed biomass, and the variation in seaweed composition can influence seaweeds ethanol production potential. Seaweed reproduction is discussed in Section 2.1, composition is discussed in Section 2.2, the general methods used for farming seaweed are explained in Section 2.3, and near shore seaweed farming practices in China and BC are explained in Section 2.4.

2.1 Seaweed reproduction

Depending on the species, seaweed propagates through asexual and/or sexual reproduction. Asexual or *vegetative reproduction* occurs when fragments of mature seaweed break off the main body or *thallus* and grow into new seaweed thallus that is a clone of the original. In seaweed farming, vegetative reproduction is facilitated by taking cuttings from a mature seaweed thallus and using them as seed stock for subsequent seaweed crops or by harvesting only part of the seaweed, leaving the remainder to grow again [14]. Sexual reproduction is more complex to facilitate then asexual, and it occurs through alternating generations of single chromosome or *haploid* cells and double chromosome or *diploid* cells.

In sexual reproduction, seaweeds alternate between generations of haploid cells and diploid cells called *gametophytes* and *sporophytes*. The haploid form is called a *gametophyte* because it will produce gametes (eggs and sperm) that fuse to form the next diploid generation, and the diploid form is called a *sporophyte* because it will produce spores that contain new haploid cells. The large, multicellular structures we recognize as seaweed can be either sporophytes or gametophytes depending on the species. Many brown seaweed species desirable for energy production, like the Laminaria species, reproduce through a dominant generation of sporophytes and a diminutive generation of gametophytes. The gametophytes are microscopic, containing only a few cells and they exist only to facilitate gamete production, and the sporophytes are large, multicellular structures that we recognize as seaweed.

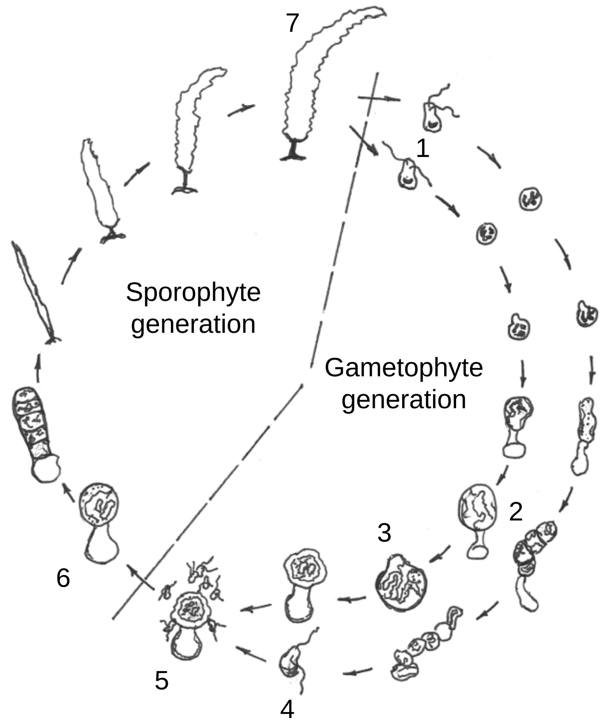


Figure 2-1: Laminaria reproductive cycle [19]

The Laminaria reproductive cycle is shown in Figure 2-1. Reproduction begins with the release of spores from the mature seaweed frond (1). The spores drift through the water and anchor to the first suitable surface they contact, like bare rock. Once anchored, they mature into ether a male or a female gametophyte (2). The female gametophytes develop a single egg (3), and the males produce and release sperm (4) that seek out and fertilize the egg (5). This fertilized egg is now the first cell of the sporophyte generation (6). The newly formed sporophyte or *sporeling* remains attached to the original anchor site where its egg was attached, and the sporeling matures into what we recognize as seaweed (7). Once mature, the seaweed develops and releases spores (1) and the cycle repeats. In *annual* seaweed species like *Nereocystis luetkeana*, the mature seaweed only lives for one year, and dying after spore release. In *perennial* seaweeds like *Macrocystis integrifolia*, the mature seaweed can live for many years and produce several generations of sporelings.

To facilitate sexual reproduction, the spore bearing sections of mature sporophytes must be harvested before spores are released, and spore release, fertilization, and initial sporeling growth must be facilitated in an illuminated and temperature controlled tank of seawater as detailed in Section 2.4.

2.2 Seaweed composition variation

Seaweed composition is highly variable; it depends upon the environmental conditions under which the seaweed grows and can be driven by natural growth cycles in some seaweed. The seaweed *Saccharina latissima* is used to illustrate the magnitude of yearly composition variation, the effect of site selection on composition, and the natural cycle of carbohydrate storage shown in several seaweed species.

2.2.1 Seasonal composition variation

Freshly harvested seaweed, referred to as *fresh* seaweed, is typically 85% water by mass, but its moisture content can range from 70% to 90% [5]. In brown seaweed, the remaining mass or *solids* is composed of ash and seven energy rich components: laminarin, mannitol, alginate, protein, cellulose, fucans, and lipids [11]. Ash content is generally very high, ranging from 22% to 37%. Laminarin, mannitol, and alginate can be fermented into ethanol [9][12] and the portion of seaweed solids made of these three components is referred to as the *fermentable fraction*. Combined, total solids and fermentable fraction determine the ethanol production potential of a given mass of fresh seaweed.

Solids content and fermentable fraction can vary significantly throughout the growing season as illustrated by the seaweed *Saccharina latissima*. Composition data is provided by Black [6][20], who studied the composition of several brown seaweed species in Scotland for a two year period. Samples of *Saccharina latissima* were taken on a monthly basis from Eilean Coltair in Loch Melfort, called the *inlet location*, and at a more open site near Shuna Island, called the *open ocean location*. The inlet location is about 38 km from the open ocean location. Data from the inlet study is shown in Figure 2-2. For the 1947 inlet samples, fermentable fraction ranged from 25% to 59% throughout the year and solids content ranged from 10% to 21% giving a significant variation in ethanol production potential.

2.2.2 Influence of environment on composition

Because fermentable fraction and solids content are influenced by local environmental conditions, ethanol production potential is linked to the site where seaweed is grown. In their

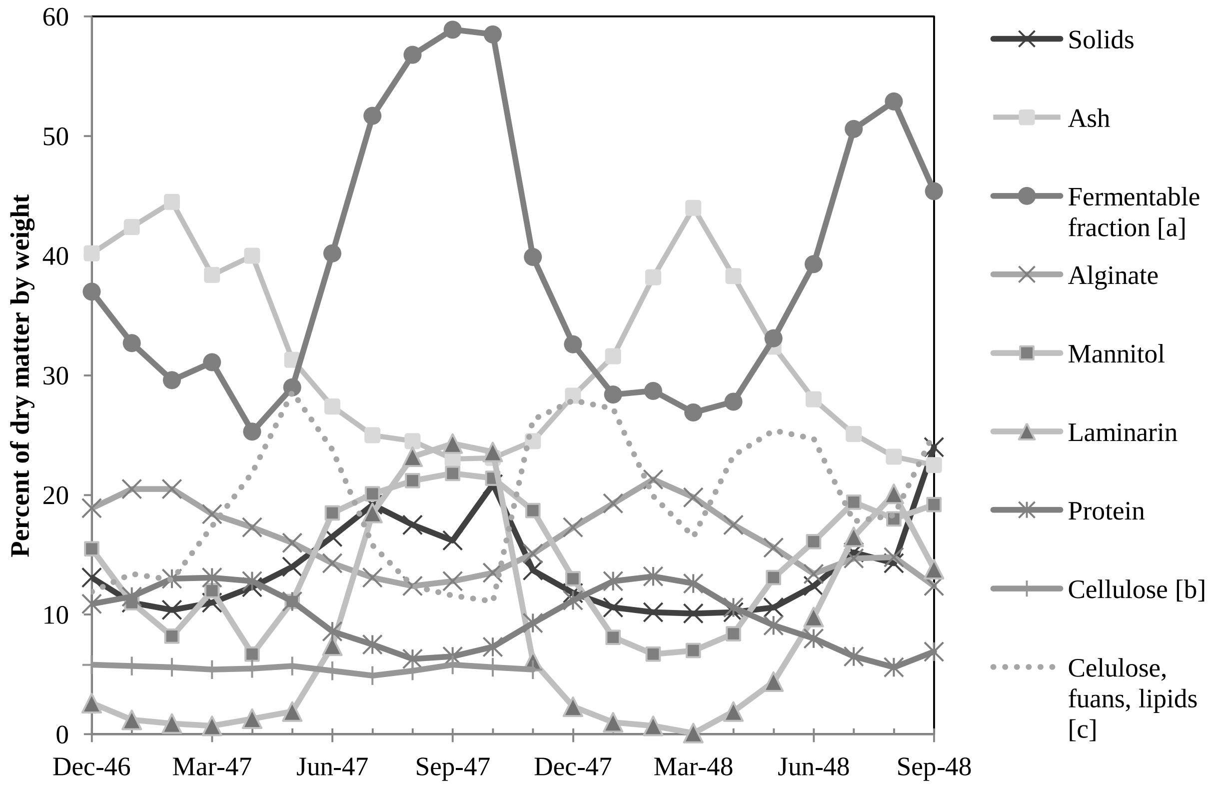


Figure 2-2: Saccharina latissima composition [6][20]. [a] Fermentable fraction is the sum of alginate, laminarin, and mannitol content. [b] Cellulose data is for Dec 45 to Nov 46 [20]. [c] The fraction of dry mass unaccounted for by Black is assumed to be composed of cellulose, fucans, and lipids as per the typical components of brown seaweed given by Percival [11].

numerical model of *Saccharina latissima* growth, Broch et. al [21] identified four main factors that affect growth and composition: water temperature, solar irradiance, water current speed, and nutrient concentration. They also identified salinity, water turbidity, and light spectral distribution as potential factors but did not model them due to lack of available data or potentially low influence. Considering the example of *Nereocystis luetkeana*, seaweed composition might also be affected by the hydrodynamic forces that result from farm structure dynamics and ocean drag. Under natural growing conditions, the seaweed *Nereocystis luetkeana* alters its morphology in response to its local hydrodynamic environment [22], changing shape and structure to accommodate local drag forces.

Comparing *Saccharina latissima* from the inlet and open ocean locations described in Section 2.2.1, solids content and fermentable fraction for the inlet location varied by up to 23%

and 48% respectively between years for the same month sampled, and they varied by up to 33% and 26% respectively between the inlet and open ocean location for the same year and month sampled. Composition for the two sites is compared in Figure 2-3. The variation between sampling year was likely caused by differences in available sunlight as 1947 was a particularly good growing year with considerable sunshine and 1948 was a very poor year with considerable cloud and rain [6]. The difference between sampling locations could have been caused by differences in local ocean conditions alone. The solar flux and weather conditions experienced at the two locations were likely similar because the sampling locations were only 38km apart.

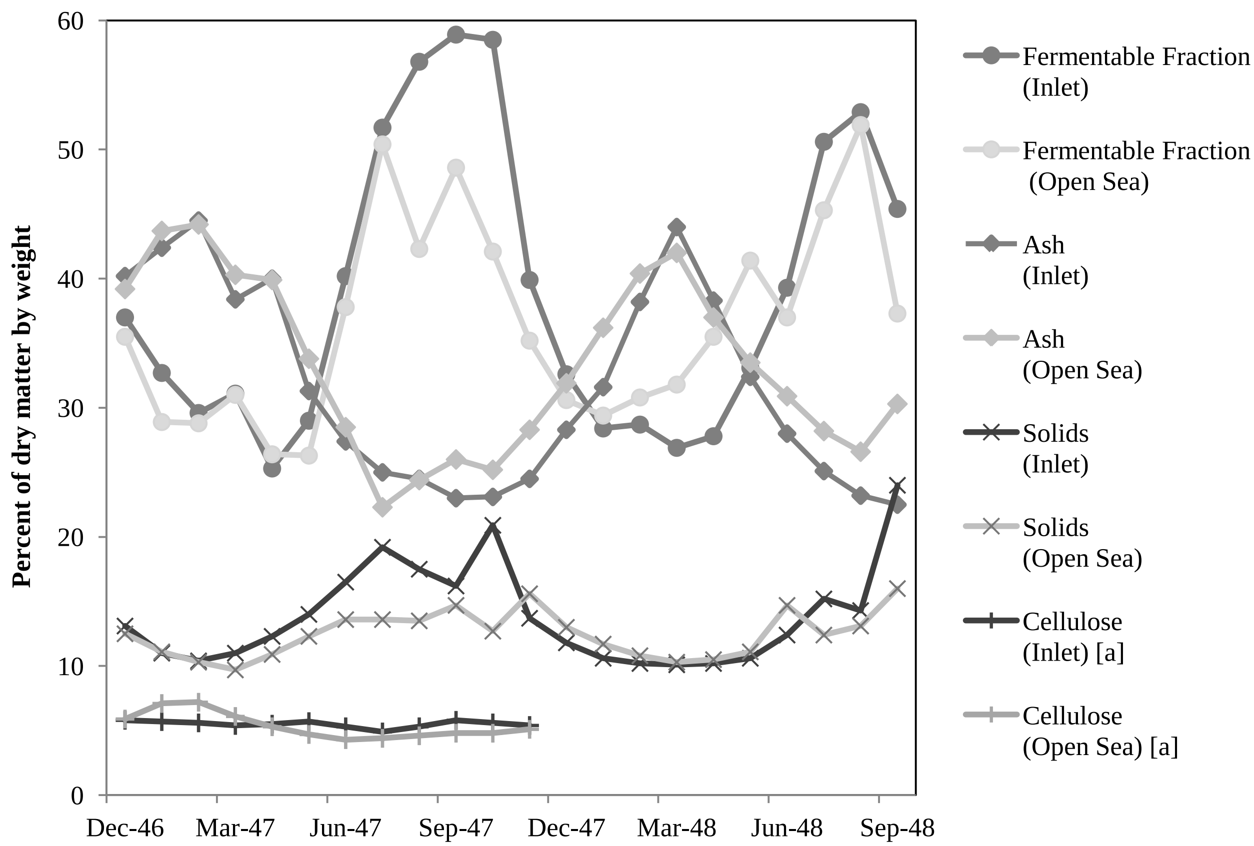


Figure 2-3: Variation in *Saccharina latissima* composition, inlet vs. open sea [6][20]. [a] Cellulose data for Dec 45 to Nov 46.

Because growth environment can influence solids content and fermentable fraction, seaweed farm site selection could have a significant impact on ethanol production potential and timing of seaweed harvest. Combined with a model of local weather and ocean conditions, a growth model like that developed by Broch et al. may provide a means to predict seaweed composition, optimum harvest period, and ethanol production potential for a given seaweed growth site, and it could be used as a screening tool to select optimum farming sites.

2.2.3 Seasonal growth cycle

Many perennial brown seaweeds, like *Saccharina latissima,* follow an alternating pattern of growth and energy storage that is advantageous for ethanol production. In northern and southern latitudes with reduced daylight in winter months, dissolved ocean nutrient levels are often maximum in winter when light levels are low but minimum in summer when light levels peak. This pattern is detrimental to seaweed growth as low light restricts growth in winter when nutrients are available while low nutrient level restricts growth in summer when light is available. To deal with this disparity, *Saccharina latissima* will limit its structural growth in spring, even if sufficient nutrients are available, and will focus on the production of the carbohydrates laminarin and mannitol to store energy when light is available. Then in winter when nutrient levels are high, energy stored in these carbohydrates is used to drive structural growth and to store additional nutrients, giving the seaweed an advantage the following summer. This cycle results in a simultaneous peak of solids content, fermentable fraction, and total biomass at the end of summer that is advantages for ethanol production. In *Saccharina latissima* this cycle is likely triggered by fluctuations in day length rather than by fluctuations in ocean nutrient concentration [23].

2.3 General seaweed farming techniques

Seaweed biomass can be generated in four ways: harvest of natural stocks, near shore farming, offshore farming, and land based cultivation. For ocean based seaweed production, natural stocks provide only 6% of global seaweed harvest and offshore farming is still only experimental, leaving near shore as the dominant form of production [5]. Land based farming is used at small scale for specialty markets [7]. Near shore farming is labor intensive, and the bulk of production is done in areas where labor cost is low. Optimum seaweed production technique varies with the region where seaweed is produced and it influences the cost, energy input, and GHG emissions associated with seaweed production. Natural stock harvest will likely make a minor contribution to seaweed ethanol production, therefore, only seaweed farming is considered in the model developed in Chapter 4. Near shore, offshore, and land based farming are discussed below.

2.3.1 Near shore seaweed farming

Near shore seaweed farming is done with two general methods: *hanging kelp rope systems* (Figure 2-4A), and *horizontal kelp rope systems* (Figure 2-4B). Hanging systems contain a long floating line (4) that is anchored to the sea floor (1) with anchor lines (2) and suspended from floats (3), and they have several vertical sections of rope (5) that hang down into the water to which the seaweed (6) is attached. The ropes are kept vertical by weights attached to their tips (7). Horizontal systems contain similar anchors (1), anchor lines (2), floats (3), and floating lines (4), but in these systems, multiple floating lines are connected to each other with horizontal ropes (8) to which the seaweed is attached. Seaweed species without natural floats like *Saccharina latissima* hang vertically from the horizontal ropes due to their own weight.

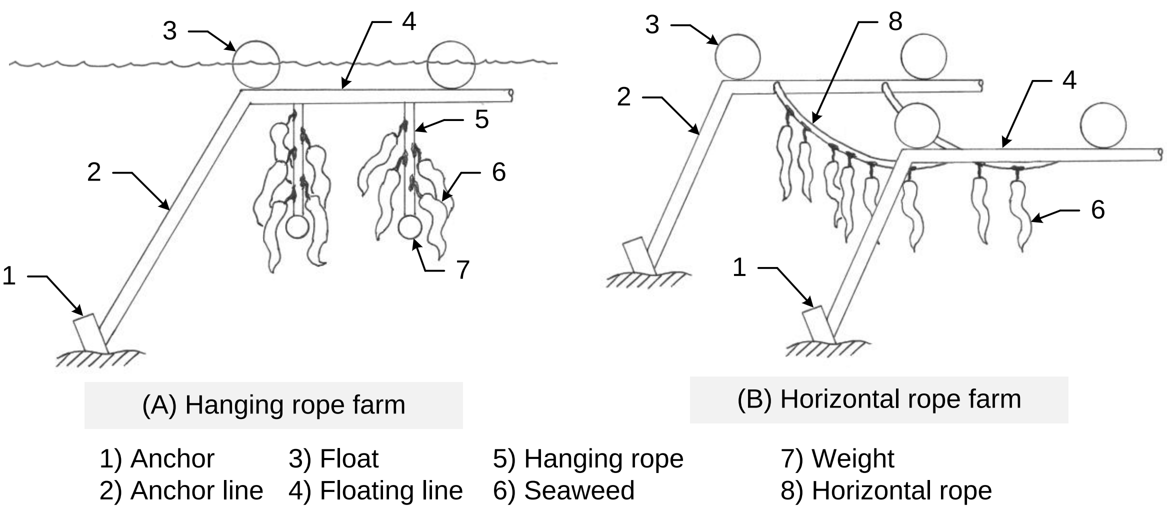


Figure 2-4: Hanging and horizontal rope seaweed farm systems [19]

Seaweed farms contain both *single raft* units as shown Figure 2-5A and *raft blocks* shown in Figure 2-5B. Single raft units are more stable due to a larger number of anchor points per floating line and are typically used in more exposed areas to deal with strong currents and wave action. They can be used as a breakwater to shelter raft blocks from strong currents or waves in large seaweed farms as shown in Figure 2-5C. Floating line length and spacing between the single raft units is determined by environmental conditions at the site [19]. Raft blocks are similar to single raft units, but they have a larger number of floating lines per anchor point. Raft blocks contain 10-40 floating lines each 45-55m long, with a 3-5m horizontal spacing [19], and

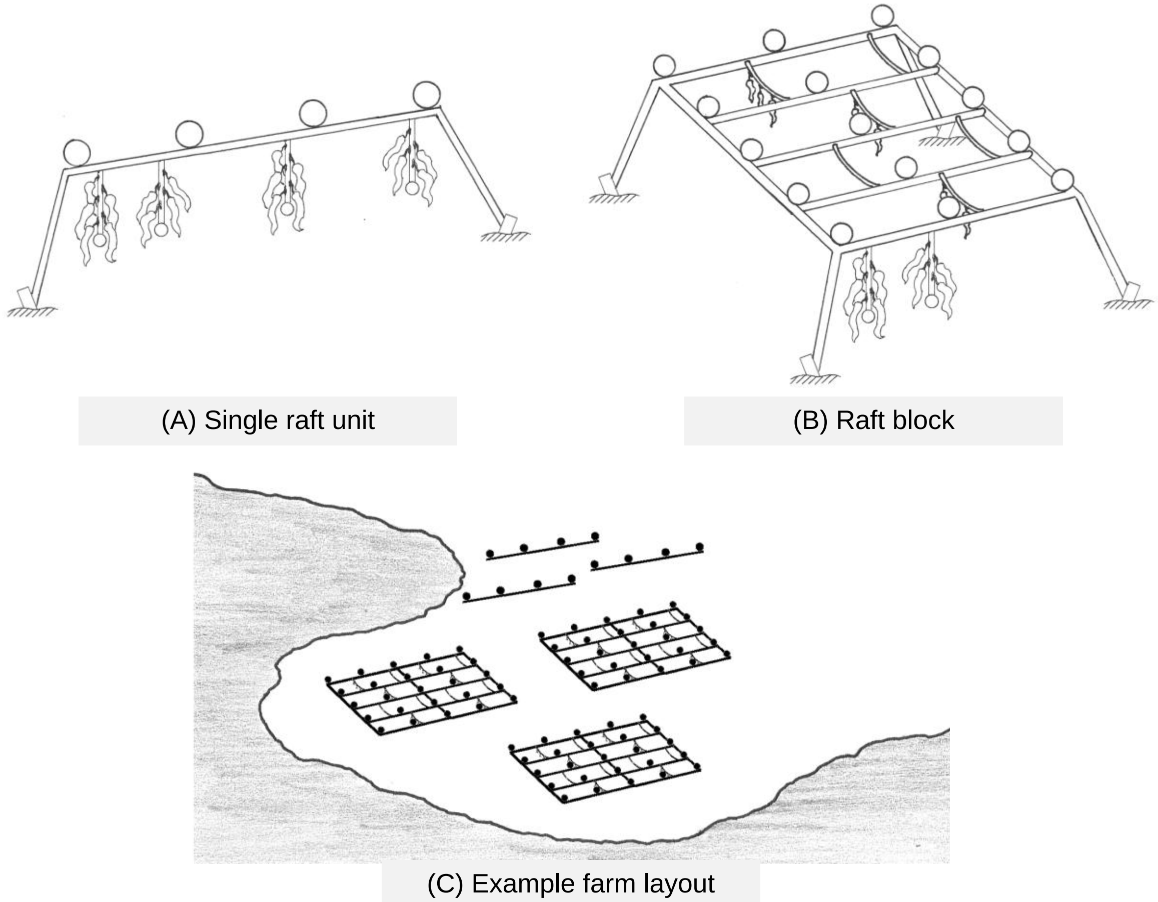


Figure 2-5: Single raft units, raft blocks, and example seaweed farm layout [19]

they contain only a few anchors. Blocks are spaced 30-40m apart for safety and to allow proper water circulation. Raft block geometry is also determined by site conditions. The floating lines can support ether hanging kelp ropes or horizontal kelp ropes. In BC, horizontal ropes must be spaced between 1 and 2 meters from each other for proper water circulation depending on local currents [24][25]. An example farm layout containing both single raft units and raft blocks is shown in Figure 2-5C.

2.3.2 Offshore seaweed farming

Offshore seaweed farming covers a range of potential biomass production systems from near shore farming systems implemented a significant distance away from shore to self contained sporeling production and farming structures with their own power generation and propulsion systems. Offshore farming systems are reviewed by Bruton et al. [5], Roesijadi et al. [7], Chynoweth [13], and Aizawa et al. [17]. These systems could open potentially limitless area for energy production in the open ocean, and oil rigs, offshore wind farms, and emerging wave energy systems demonstrate the potential feasibly of such structures. However, open ocean systems are expensive to construct and maintain and seaweed biomass has relatively low value per unit of ocean structure when ethanol production is considered. Offshore systems could be combined with offshore wind farms [5] or other existing ocean infrastructure to reduce their overall cost. Offshore farms are a promising concept, but additional work is required to prove their feasibility in difficult ocean environments and to prove offshore systems can produce cost competitive ethanol feedstock.

2.3.3 Land based cultivation

Land based culture of seaweed achieves greater control over growing conditions, but it at much higher production cost and potentially high energy cost. Roesijadi et al. [7] lists the advantages of on land systems being 1) ease of seaweed management; 2) use of seaweeds with or without holdfast structures; 3) ease of nutrient application without dilution; 4) avoidance of open sea problems such as bad weather, disease, and predation; and 5) possibility of locating farms near conversion operations. Land based culture is currently used for specialty seaweed products like food and cosmetics [26], but it is likely difficult to design an affordable system for biofuel production. For the case study considered in Chapter 5, one tonne of dry seaweed produces $230 worth of ethanol, but the same seaweed could be sold for $48,000 dollars or more in the food market [25]. Therefore, systems suitable for high value seaweed products like food may not be cost effective for biofuel production due to the relatively low value of ethanol. In addition to effecting cost, land based culture systems require energy input for water circulation and lighting that may degrade lifecycle performance. In their analysis of ethanol production, Peter et al. [18] found that water circulation in cultivation tanks was a significant contributor to lifecycle energy input. Because the energy content of fresh seaweed biomass is low due to seaweed’s high ash and water content, a small amount of energy input per unit of fresh biomass may significantly increase lifecycle energy inputs and GHG emissions for seaweed ethanol.

2.4 Near shore farming practices in China and BC

The culture of *Laminaria japonica* in Northern China begins with frond collection in mid-July. Spore bearing fronds are partially dried to stimulate spore release and placed in a culturing tank that is cooled to 8-10°C. The male and female spores anchor to palm fiber mats in the tank where they generate the next generation of sporelings as described in Section 2.1. The tank is illuminated by natural light in a greenhouse like structure, and light levels are controlled by shade cloth. The sporelings grow here for 3 months until they 2-5 cm long, large enough to transfer to intermediate growing rafts in the ocean. At the intermediate rafts, they grow for an additional 2-4 weeks until reaching 10-25 cm in length, and they are finally transferred to permanent growing ropes in the ocean where they mature into a seaweed crop over the next 8 months. Additional cultivation during this growth period can be required. For example, at sites with significantly turbid waters, the seaweed must be agitated to remove sediment buildup that can block light and restrict growth [19].

In the seaweed farming system practiced in BC by Cross [24], seaweed production begins in late September with a similar collection of spore bearing seaweed fronds. The fronds are placed in a tank of sterilized seawater where spore release is chemically induced. The spores anchor to lengths of twine and generate sporelings that remain attached to the twine. The tank is artificially illuminated, electrically heated, and its water is circulated for 6-8 weeks while the sporelings grow to a length of 1-2mm. The twine segments are then installed on floating ropes at a farm structure in the ocean, and the sporelings grow into mature seaweeds over the next 7-8 months without additional cultivation. Growth is negligible overwinter, but increases rapidly in March when light levels increase and the mature seaweeds peaks in biomass content near the end of July.

2.4.1 Fertilizer application

Fertilizer application has an unknown effect on seaweed production GHG emissions, but it is only required in Northern China and is not typically required in BC. In Northern China, it is common to apply nitrogen fertilizer during all stages of seaweed growth in areas where the natural ocean nitrogen level is low, but no studies examining the GHG emissions of this practice could be found. In *Laminaria japonica* production, ammonium nitrate is sprayed in the water near the seaweed if natural nitrogen levels are less than 100 mg/m^3. As seaweeds rapidly absorb this nitrogen and store enough for several days of growth, fertilizer is only applied every few days [19]. There is potential for this practice to greatly increase the lifecycle emissions of seaweed ethanol. In corn ethanol production examined by Bremer et al. [16], nitrogen fertilizer use and associated N_2O emissions were responsible for 36% of total GHG emissions. As the practice of land and ocean fertilization are physically quite different, emission levels per kg of fertilizer applied on land likely do not translate to ocean application. Seaweed production in Southern China and in BC does not typically require fertilizer [19][24] as natural ocean nitrogen levels are sufficient for seaweed growth.

2.5 Summary

As demonstrated in this chapter, seaweed biology can influence seaweed ethanol production in several ways. Seaweed solids content and fermentable fraction determine ethanol production potential of seaweed biomass, and both are functions of environmental conditions where the seaweed grows. They can also vary significantly throughout the year. Seaweed can be farmed with near shore, offshore, or on land farming systems, and the system chosen will influence production cost, energy input, and GHG emissions associated with seaweed production. Farming technique varies depending on the region of seaweed production, and fertilizer use for seaweed farming is a potentially significant source of GHG emissions that remains to be quantified.

The following chapter deals with farmed seaweed after harvest, giving background information for the conversion of seaweed biomass into ethanol and giving background information on ethanol production in general.

3 Background on ethanol production

Chapter 3 provides an overview of fermentation based ethanol production and examines the specific case of fermentation based ethanol production from seaweed biomass. Ethanol is a two carbon alcohol with a variety of uses which include being a solvent, a beverage, and a high octane fuel for spark ignition engines. Ethanol can be thermochemically synthesized from syngas produced from biomass [27], natural gas, coal [28], or almost any other hydrocarbon source. It can be biologically synthesized from syngas [29], and it can be directly produced and secreted by genetically engineered photosynthesizing organisms [30]. However, ethanol is most commonly produced by microbial fermentation of sugars. In this process, sugars are consumed by the microorganisms as an energy source, and ethanol is excreted as a metabolic byproduct. This process can be used for a variety of feedstocks with a variety of processes, but most fermentation based ethanol systems share several common production steps and they are commonly limited by the natural availability of feedstock. Production is broken into seven steps that are common to ethanol production from most feedstocks, and the seven steps are illustrated with the case of dry grind corn ethanol production. Ethanol plants require a nearly year round supply of feedstock, but fresh feedstock is usually not available. Saccharide crops are often only optimal for ethanol production during a short period in their natural lifecycle called the *harvest season*. Three techniques for ensuring adequate feedstock supply for crops with a short harvest are discussed. As seaweed can also experience a limited harvest season, the three compensation techniques are examined in the context of seaweed ethanol production. Ethanol yield from seaweed is also discussed. Section 3.1 covers the seven steps of fermentation based ethanol production and the dry grind corn ethanol process, Section 3.2 discusses the techniques used to deal with feedstock harvest season, and seaweed ethanol is discussed in Section 3.3.

3.1 General ethanol production process

Fermentation based ethanol production contains seven general steps shown in Figure 3-1. The seven steps of solar energy capture, biomass supply, saccharide extraction, hydrolysis, fermentation, recovery, and residue processing are explained below, and the process of dry grind corn ethanol production is illustrated in Section 3.1.8 using these steps.

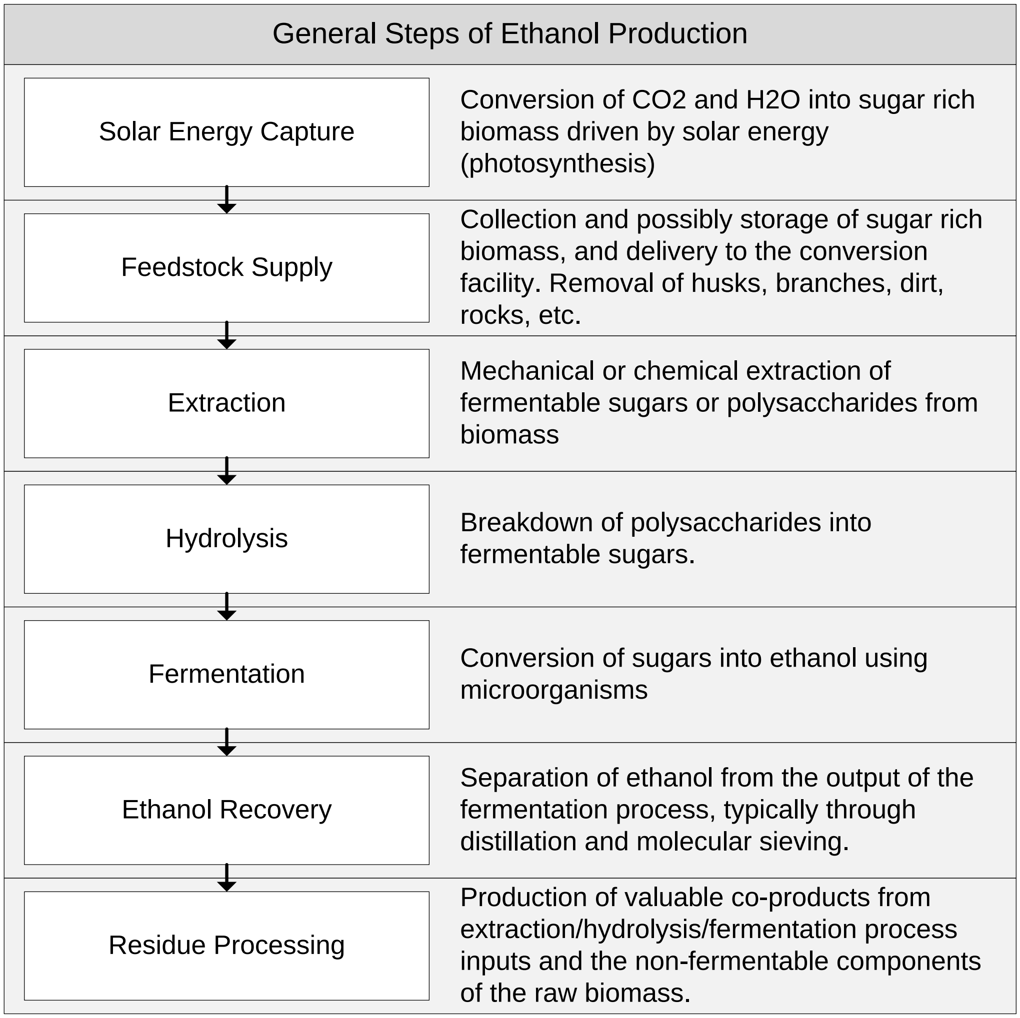


Figure 3-1: General steps of fermentation based ethanol production

3.1.1 Solar energy capture

Bioethanol production begins with solar energy capture. In this step, photosynthesizing plants, algae, or bacteria convert the energy in solar radiation to temporary chemical bonds and perform a series of chemical reactions with that energy to combine water and CO_2 into hydrocarbons. The process of photosynthesis begins with the creation of glyceraldehyde-3-phosphate (G3P) which is subsequently used to produce short, energy rich hydrocarbons called simple sugars or *monosaccharides*. Common examples include glucose and fructose (both $C_6H_{12}O_6$). Photosynthesizing organisms will often polymerize these monosaccharides through multiple dehydration reactions. The resulting *polysaccharides* are used as a dense energy storage mechanism or as structural elements. Examples of polysaccharides made from glucose include the energy storage polymers amylose and amylopectin (i.e. starch) and the structural polymer cellulose. Monosaccharides and polysaccharides are referred to generally as *saccharides*. G3P is the main target of ethanol production, as fermentation is ultimately a process to convert saccharides into G3P then to convert G3P to ethanol and CO_2.

3.1.2 Biomass supply

In addition to saccharide production, photosynthesizing organisms use the solar energy stored in G3P and previously produced saccharides to synthesize an assortment of organic molecules including proteins, lipids, and nucleic acids that make up their overall structure. They also use that energy to capture an assortment of minerals and elements necessary for life and to absorb water. This collection of saccharides, organic molecules, and other components is commonly referred to as *biomass*. Photosynthesizing organisms like plants are typically spread over a large area and many only achieve high saccharide composition for a short period each year.

To facilitate ethanol production, biomass must be harvested, consolidated, pretreated and delivered to the ethanol production facility. Pretreatment can include removal of husks, branches, leaves, and other biomass components with a low concentration of targeted saccharides and the removal of dirt, sand, rocks, or other contaminants that may hinder further processing, and it may include measures to ensure a year round supply of feedstock to the conversion facility. The issue of year round feedstock supply is dealt with in detail in Section 3.2.

3.1.3 Saccharide extraction

Once delivered to the ethanol conversion facility, saccharides that will eventually become ethanol are generally hidden within the larger structure of the delivered biomass, and they must be extracted before ethanol production can begin. Saccharides are generally extracted into an aqueous solution in preparation for hydrolysis and fermentation. This process ranges in complexity from the relatively simple process of crushing sugarcane to extract saccharide rich juice to the relatively difficult chemical extraction of cellulose from cellulosic biomass [31]. Saccharides usually remain in a mix of non-fermentable biomass components after saccharide extraction, but if the expense of separation can be justified, proteins, lipids, or other biomass components can be separated from the saccharides as ethanol *co-products* at this stage in production. Corn oil is produced this way through the wet grind process [32].

3.1.4 Hydrolysis

Once extracted, monosaccharides can be directly fermented, but polysaccharides must be depolymerized back into monosaccharides before fermentation. All polysaccharides are formed by dehydration reactions and they are all depolymerized through hydrolysis reactions. Hydrolysis can be done biologically using polysaccharide specific enzymes, like cellulase to break down cellulose or amylase to break down amylose and amylopectin, or it can be done thermochemically with processes like acid hydrolysis and supercritical water hydrolysis [33] [34]

3.1.5 Fermentation

Together, saccharide extraction and hydrolysis produce an aqueous solution of monosaccharides and unfermentable biomass components called *mash*. Microorganisms are added to the mash, and they consume the monosaccharides as a source of energy, secreting ethanol back into the solution as a metabolic by-product. Typical fermentation organisms use the glycolysis process to divide each monosaccharide into two molecules of G3P and to convert G3P to pyruvate. This is followed by a two step fermentation reaction to convert pyruvate into CO_2 and ethanol. The chosen microorganisms must be appropriate for the feedstock being converted, as individual microorganisms are limited in the types of monosaccharides they can metabolise and by the mash environment in which they flourish. For example, glucose and fructose are commonly fermented by the yeast *Saccharomyces cerevisiae* at a pH of 4.5 and a temperature between 27 and 32°C [35], and the seaweed monosaccharides released in alginate hydrolysis can only be fermented by genetically engineered microorganisms [4][12].

After the monosaccharides have been completely converted to ethanol, the mash is called *beer*. As the monosaccharide source is finite and ethanol is toxic to fermenting organisms in sufficient concentration, fermentation ends when ether the monosaccharide source is depleted or when ethanol concentration in the mash reaches toxic levels. Final concentration in corn ethanol production is typically 8-10% ethanol by weight or 10-12% by volume [35], but higher concentrations have been achieved [36].

3.1.6 Ethanol recovery

To be useful as a vehicle fuel, ethanol must be recovered from the beer. Recovery typically has two stages: distillation to produce a mix of water and 91% ethanol by weight and molecular sieving to increase the concentration to 99.6% ethanol [35]. If this *anhydrous ethanol* is to be used for vehicle fuel, it must be mixed with gasoline to make *denatured ethanol* that is legally distinct from ethanol for human consumption. Denatured ethanol is typically 3% gasoline by volume (2.7% gasoline by mass) [16]. A diagram of the recovery process is shown in Figure 3-2.

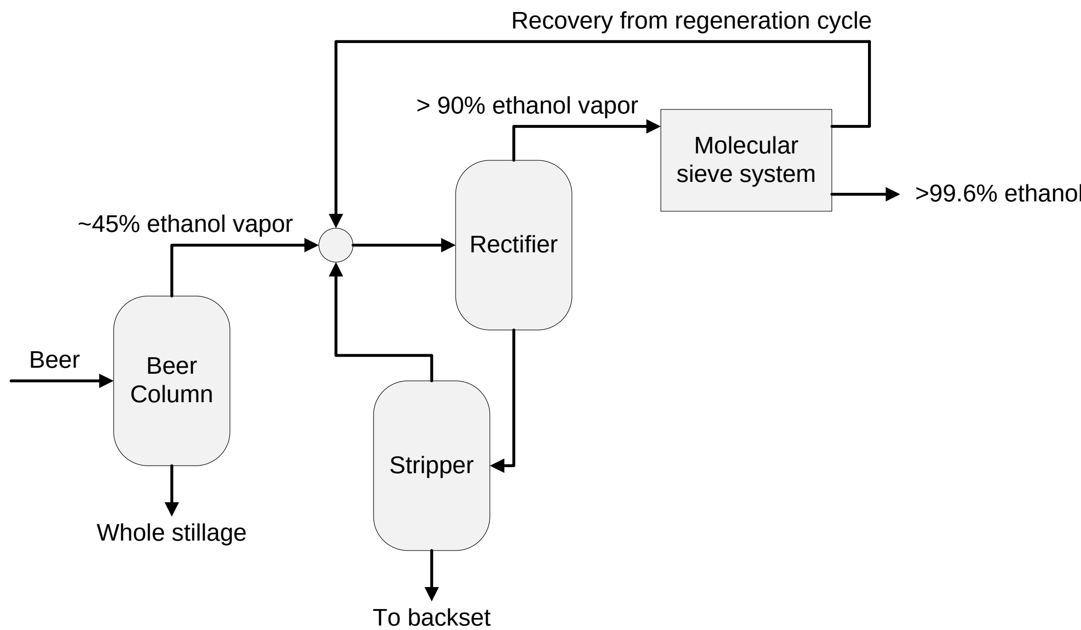


Figure 3-2: Simplified diagram of ethanol recovery process [35]

3.1.7 Residue processing

After ethanol has been recovered, unfermentable components from the original biomass, process additives like hydrolysis enzymes, and microorganism biomass generated during the fermentation process remain as *distillation residue*. This residual mass of fats, protein, minerals, and unfermentable saccharides can be processed into a variety of ethanol co-products depending on the original feedstock composition. In corn ethanol production, whole distillation residue is commonly dried and sold as an animal feed called *distiller's grains*.

General Steps of the Dry Grind Corn Ethanol Process		
Solar Energy Capture	Photosynthesis Produce Starch Grow Corn Kernels	As the corn plant grows, it captures solar energy though photosynthesis and produces glucose then amylose and amylopectin, aka corn starch. The starch is then bound in unfermentable fiber, protein, and fat within corn kernels.
Feedstock Supply	Harvest, extraction, storage, delivery, and cleaning of Corn Kernels	The corn plant is harvested and the corn kernels are removed and dried. The dry kernels are stored in grain silos and are delivered to the ethanol plant as required. Before extraction, broken kernels, dirt, and other foreign materials are removed from the kernels by screens and blowers.
Extraction	Grind Corn Kernels into corn Grains	The kernels are ground into a course flour or grain containing 0.5-2mm particles to expose the corn starch.
Hydrolysis	Liquefaction Convert Starch in corn grains to soluble Dextrins Saccharifaction Convert Dextrins to Glucose	The corn grain is mixed with water and the exposed corn starch is enzymatically decomposed into monosaccharides through a two stage process. First, the starch is paritially broken down into to short, water soluble glucose chains called dextrins with alpha-amylase. This is followed by a complete breakdown of the dextrins into glucose with beta-amylase. The fist process is called liquefaction and it takes 1 hour at 88°C and a pH of 6.5. The second step is called saccharifaction and it takes 5-6 hours at 60°C and a pH of 4.5.
Fermentation	Convert Glucose to Ethanol	The newly produced glucose is consumed and converted into ethanol by the yeast S. Cerevisiae. S. Cerevisiae must be kept between 27-32°C for optimal conversion. The process takes 46-68 hours and produces a beer containing 10-12% ethanol by volume.
Ethanol Recovery	Extract fuel grade ethanol	Ethanol in the beer is removed and purified though a combination of distillation and Molecular Sieving. Distillation produces at 91% ethanol/water mixture by weight, and molecular sieving improves the concentration to 99.6% ethanol.
Residue Processing	Centrifuging and Drying to produce Distillers Grains	After ethanol recovery, the residue composed of water, unfermentable fiber, protein, and fat from the raw corn kernel, S. Cerevisiae biomass, and processing additives is commonly dewatered and dried to form a course yellow animal feed called distiller's grains.

Figure 3-3: Dry grind corn ethanol process [16][35]

3.1.8 Dry grind corn ethanol production

The dry grind process is one of the most common ethanol production processes, accounting for over 32% of world ethanol production [37]. The seven steps of ethanol production are shown for the process of dry grind corn ethanol production in Figure 3-3.

3.2 Dealing with feedstock harvest season

Ethanol plants must operate almost year round to maximize the significant capital investment involved in their construction, but feedstock of acceptable size and fermentable fraction are typically only available for a few months of the feedstock crop’s natural lifecycle. Three methods are currently used in the corn and sugarcane ethanol industries to deal with this discrepancy and maintain an adequate feedstock supply: feedstock storage, harvest extension, and use of additional feedstock.

3.2.1 Storage

Storage involves drying or otherwise stabilizing ethanol feedstock during its harvest season and storing the stable feedstock until it is required for ethanol production. In the example of corn ethanol production, corn kernels are only available for a few months in the fall. The fall crop is dried and stored in large silos where they remain preserved for a year or more, and dry kernels are removed from storage and used for ethanol production thought the year as required

3.2.2 Harvest extension

Depending on the crop, it is possible to create an extended harvest season through two cultivation practices: staggered planting and planting multiple varieties. This is well illustrated by sugarcane ethanol production which uses both techniques. Sugarcane is broadly classified into early, mid-late, and late maturing varieties that mature after 12, 14, and 16 months respectively [38], and a 30:40:40 ratio of the three varieties is typically planted in any given sugarcane plantation. Each variety is planted in small groups at regular intervals from May until October [39]. This staggered planting ensures that mature sugarcane is continuously available from April to December in the following year.

3.2.3 Additional feedstock

If feedstock with acceptable fermentable fraction is not available during part of the year, and if storage or culturing practices cannot fully compensate, an additional feedstock with ether a complementary harvest season or better storage characteristics can be used. For example, sugarcane ethanol plants typically shut down for 5 months at the end of December because harvest extension cannot provide a year round supply of fresh feedstock. As sugarcane and cane juice are both impractical to store, processing stored corn kernels as an additional feedstock has been proposed as a method to keep sugarcane ethanol plants operating during this five month shutdown [40]. Sugarcane saccharide extraction equipment would remain idle, but fermentation and ethanol recovery equipment could potentially be used for both sugarcane processing and corn processing.

3.3 Seaweed ethanol production

Both seaweed harvest season and seaweed ethanol yield must be addressed, to understand seaweed ethanol production, as harvest season can be limited, and yield is significantly influenced by fluctuations in seaweed composition. For the seaweed *Saccharina latissima* grown in BC, storms, low light, and high rainfall in winter and the natural growth cycle discussed in Section 2.2.3 limits seaweed production to a single crop each year that is optimum for harvest during a 1-2 month period in summer [24]. Ethanol yield is also an important issue that has received considerable attention in the literature, but the literature is of limited use for modeling seaweed ethanol production in general because composition fluctuation is not considered. The three techniques of storage, harvest extension, and additional feedstock are discussed as they apply to seaweed to address seaweed harvest season, followed by discussion of seaweed ethanol yield and proposal of a tool to estimate ethanol yield from any brown seaweed that accounts for composition variation.

3.3.1 Dealing with seaweed harvest season

Seaweed may suffer the same harvest season limitations of corn and sugarcane, but the techniques used in corn and sugarcane ethanol could be used to extend harvest season. Depending on the species, seaweed may only be harvestable for a few months during the year [19][24], and seaweed begins to decompose within a few days of harvest [5][24]. Feedstock storage, harvest extension, and/or additional feedstock may be required to provide ethanol plants with a year round supply of seaweed feedstock. Seaweed can be stored dry or wet, and there may be opportunity for extended harvest in tropical regions, but the use of additional feedstock is likely not possible unless combined with the other two techniques.

3.3.1.1 Storage

Seaweed is storage stable when dried below 22% moisture, and dry seaweed can be stored for a year or longer [19]. Drying can be done with a mix of technologies from simply spreading the seaweed on a flat surface to dry in the sun to sending the seaweed through multistage steam powered drying systems powered by natural gas or coal. Because seaweeds typically contain 70-90% water when freshly harvested [5], drying consumes an enormous quantity of energy per unit of seaweed solids. Bruton et al. [5] noted that mechanical dewatering could be used to reduce energy use in drying; however, dewatering may result in a significant loss of fermentable fraction that was not considered. Mannitol and laminarin form a significant portion of the fermentable fraction in many brown seaweeds, and because both mannitol and some branched forms of laminarin are water soluble [9], they may be lost during dewatering. Even rinsing seaweed with fresh water or exposure to rain may reduce mannitol content [6]. Dry seaweed must be kept in an air tight or low humidity environment as seaweed will rapidly absorb moisture from the air, rehydrate, and spoil [25].

Fresh seaweed can also be stored in its natural state when combined with a mix of formaldehyde and methanol called formalin. This mixture can be safely stored for several months [41]. This eliminates the enormous energy demand of drying, but the toxicity of formaldehyde and methanol could limit the growth of fermenting organisms during the ethanol production process. This may be a promising storage method for thermochemical seaweed conversion processes.

3.3.1.2 Harvest extension

In some tropical regions, seaweed crops can mature in only 35-45 days [14]. Depending on available ocean nutrients or fertilization it may be possible to produce mature seaweed throughout the year though staggered planting, similar to the sugarcane planting described in Section 3.2.2. In higher latitudes, staggered planting is likely not possible because seaweed growth is limited in winter by low light and poor weather and because fermentable fraction can be tied to the yearly cycle of day length as described in Section 2.2.3. It may also be possible to extend seaweed harvest season by planting multiple species or strains of seaweed that mature at different rates or different times of the year.

3.3.1.3 Additional feedstock

Seaweed could be paired with storable feedstocks like corn, wheat, or cellulosic biomass to achieve year round ethanol production, but seaweed harvest season can be very short, limiting the use of seaweed in the multi-feedstock arrangement. For example, harvest season is only 1-2 months for *Saccharina latissima* in BC [24]; therefore, seaweed would produce less than 20% of total ethanol output. Additional feedstock production may need to be combined with seaweed feedstock storage or harvest extension if seaweed is to provide a significant percentage of total ethanol output.

3.3.2 Ethanol yield in the literature

Several studies have shown that ethanol production from seaweed is possible [4] [9][12]; however, ethanol yield estimates in literature are subject to significant uncertainty and are limited to a small number of seaweed species. Aizawa et al. [17] estimated the ethanol yield from Japanese Laminaria and from *Undaria pinnatifida* to be 34 L/tonne and the yield from *Sargassum horneri* to be 38 L/tonne. As noted by Roesijadi et al. [7], little background or reference is given for this estimate. Horn achieved a maximum yield of 0.43 g ethanol per gram substrate from mix of mannitol and laminarin, and 0.38g/g mannitol alone, giving a conversion of 0.10 g/g dry seaweed assuming a mannitol content of 25%. Roesijadi et al. reviewed several studies that estimated a yield from brown and red seaweeds and found values of 0.08 and 0.12 g/g dry seaweed. Roesijadi also calculated a yield of 0.254 g/g dry seaweed or 39L/tonne based on the work of Reith et al. [8], but comments that Reith's assumption of 50% conversion of the seaweed solids to ethanol is "very ambitions and still need research". Recently, Wargacki et al. [12] achieved an experimental yield of 0.281 g/g dry seaweed, showing that the estimates of Reith and Aizawa are reasonable.

These conversion estimates do not include composition data for the seaweed samples examined or details on where and when the samples were taken. As discussed in Section 2.2, fermentable fraction can range from 25% to 59% of total solids depending on time of harvest. It is unclear if the samples considered in the above yield estimates were taken while the seaweed had optimal saccharide content or not; therefore, the above conversion estimates may not represent ethanol yield from a properly executed seaweed harvest.

To deal with the limitations of available ethanol yield values, an alternate method of ethanol yield calculation is discussed as part of the well-to-wheel seaweed ethanol production model in Section 4.1.4. Ethanol yield in the context of the model is defined as *conversion rate.*

3.4 Summary

As discussed in this chapter, seaweed ethanol is produced in a similar manner to conventional ethanol and it faces similar limitations regarding feedstock supply. Fermentation based ethanol production commonly requires the seven steps of solar energy capture, biomass supply, saccharide extraction, hydrolysis, fermentation, recovery, and residue processing, and if harvest season is limited, the techniques of feedstock storage, harvest extension, and additional feedstock types can be used to provide year round feedstock supply, as required by large ethanol plants. Feedstock storage is used to deal with harvest season in corn ethanol production, and the harvest extending practices of staggered planting and planting multiple crop varieties are used to deal with harvest season in sugarcane ethanol production. The use of corn as an additional feedstock is also proposed for sugarcane ethanol production. Dry seaweed storage is promising for extending harvest season for seaweed in general and harvest extension is promising for seaweed in tropical areas. Wet seaweed storage is likely problematic for fermentation based ethanol due to formalin toxicity, but may be helpful in thermochemical seaweed processing systems. Alternate feedstock is likely not viable unless combined with feedstock storage or cultivation practices. As ethanol yield values for seaweed are limited to specific species and subject to uncertainty, an alternate method for calculating ethanol yield was proposed.

The next chapter discusses the well-to-wheel model of seaweed ethanol production that is the focus of this thesis. The model covers energy inputs, GHG emissions, production potential, and cost for seaweed ethanol, and it contains the ethanol yield estimation tool discussed in this chapter.

4 Seaweed ethanol production model

This chapter presents a general well-to-tank model for the production of ethanol from farmed seaweed. The model contains three components: Energy input and emissions, near shore ethanol yield, and cost analysis, and it produces four performance metrics: *Energy Return on energy Invested* (EROI), *Carbon Intensity* (CI), near shore ethanol yield, and maximum feedstock cost. EROI for any energy carrier production system is defined as total useful energy contained in the produced carrier divided by the total energy input required for carrier production. Similarly, CI for any energy carrier is defined as the total GHG emission during carrier production divided by the total energy input required to support carrier production. EROI is used to determine if the process of seaweed ethanol production uses more energy than is contained in the resulting ethanol, and CI is used to judge climate benefit of replacing gasoline with seaweed ethanol relative the benefit of replacement by other ethanol sources. Near shore ethanol yield measures the seaweed ethanol production potential for a given region of coastline if near shore seaweed farming is used, and maximum feedstock cost gives the maximum cost for dry seaweed that allows for affordable ethanol production.

The model description is divided into two parts. First, Sections 4.1 to 4.3 describe how the model is derived. Energy inputs, GHG emissions and co-product credits are discussed in Section 4.1 including a discussion of seaweed-to-ethanol conversion rate in Section 4.1.4. Near shore ethanol yield is discussed in Section 4.2 and cost analysis is discussed in Section 4.3. Second, Section 4.4 gives the model itself, covering definition and calculation of the four performance metrics, then covering calculation of the energy inputs, GHG emissions, and co-product credits.

4.1 Energy inputs, GHG emissions, and co-product credits

As shown in Figure 4-1. Seaweed ethanol production is assumed to require at most five processes: the production of mature seaweed from young seaweed called *sporelings*, drying the seaweed with renewable heat if seaweed storage is required, transporting seaweed feedstock to the conversion facility, converting seaweed biomass into ethanol, and distributing the ethanol for final use. These are labeled seaweed production, drying, transport and distribution, and conversion respectively.

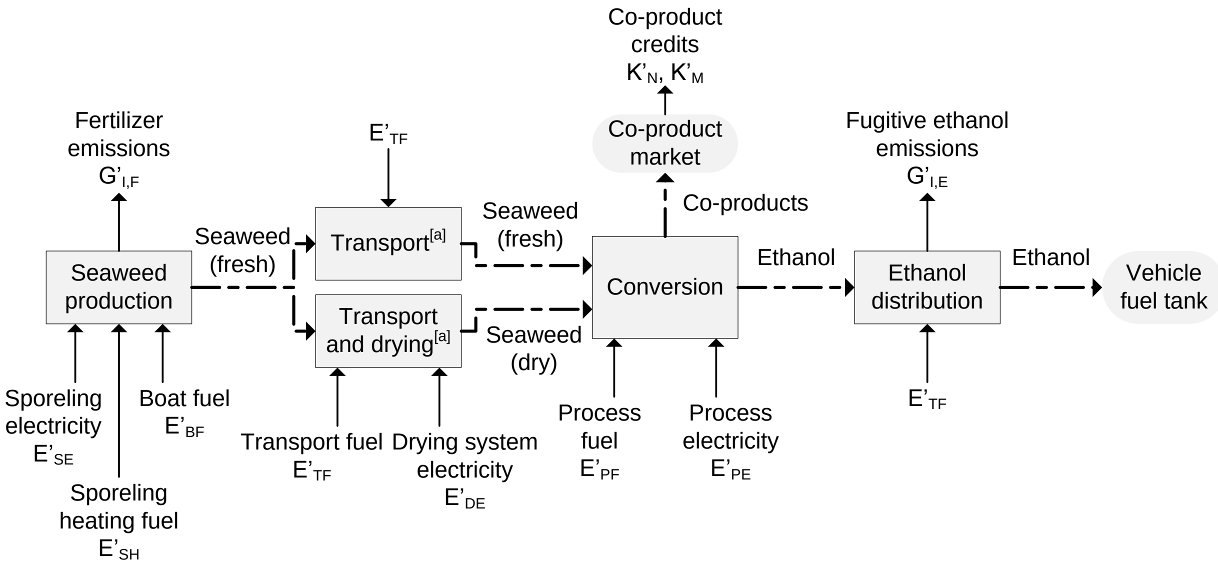


Figure 4-1: Seaweed ethanol production model. Energy inputs and indirect GHG emissions are shown with solid arrows, mass flows are shown with dashed arrows, and direct GHG emissions are omitted for clarity. [a] Depending on the region of production, seaweed may be delivered fresh for immediate conversion to ethanol or dried and stored at the conversion facility for later conversion.

The energy inputs, GHG emissions, and co-product credits for each process are divided into a number of general groups based on energy input type as shown in Figure 4-1. Energy input includes electricity and various fuels, and it is divided into sporeling electricity, sporeling heating fuel, boat fuel, drying system electricity, transport fuel, process fuel, and process electricity. GHG emissions include direct emissions from all energy inputs (omitted from Figure 4-1 for clarity) and indirect emissions from ethanol vapor losses, and they may include indirect emissions from fertilizer application during seaweed production. Co-product credits may include both energy and GHG emission credits earned by the conversion facility as explained below. The treatment of the seven energy inputs is described first followed by emissions and then by co-product credits.

4.1.1 Energy input in seaweed production

Sporeling electricity, sporeling heating fuel, and boat fuel support the tank based cultivation of sporelings and the ocean based growth of mature seaweed. Brown seaweed reproduction is discussed in Section 2.1. Assuming sexual reproduction, seaweed production is generally facilitated by collecting mature seaweed fronds before spores are released, culturing the spores into sporelings in land based tanks of seawater, and planting the sporelings on ocean based farm structures. Sporeling electricity is the total electricity input needed for cooling, lighting, and water circulation during sporeling cultivation, sporeling heating is the total fuel input (e.g. natural gas, coal) needed to maintain appropriate water tank temperature as the sporelings mature if heating is required, and boat fuel is the total fuel energy consumed while collecting seaweed spores, installing mature sporelings on farm structures, applying fertilizer as the sporelings mature if required, and performing other seaweed cultivation operations if required. Sporeling electricity and sporeling heating per unit of ethanol produced are calculated from the total electricity/heat input needed per batch of sporelings, the seaweed yield of mature seaweed per batch of sporelings, and a seaweed-to-ethanol conversion rate. Boat fuel use per unit of ethanol produced is calculated using fuel use per unit of seaweed produced and the same seaweed-to-ethanol conversion rate. Additional details on seaweed production are found in Section 2.

4.1.2 Energy input in drying

Energy input for seaweed drying is considered cases where feedstock storage is required. For efficient use of process equipment, ethanol plants require a year round supply of feedstock, but as discussed in Section 3.3.1, seaweed may not naturally meet this need without feedstock storage or harvest season extension. Harvest season extension may require additional electricity or fuel input during seaweed production, and this would be accounted for with sporeling electricity, sporeling heating fuel, and boat fuel in the preceding section. Due to the very short shelf life of fresh seaweed, some storage may be needed even when using harvest season extension. Logistical issues like equipment failure, disease, and storms will likely interrupt the supply of fresh feedstock, but stored seaweed could be used as backup feedstock supply to maintain constant ethanol production when fresh feedstock is temporarily unavailable. The case of pure harvest season extension is shown in Figure 4-1 by the transport pathway. Wet storage is not considered as the toxicity of formalin would likely inhibit fermentation. As discussed in Section 3.3.1, dry storage requires moisture content below 22%, and the process of seaweed drying requires a significant amount of energy.

Because seaweed has a very high water and ash content [5], drying seaweed takes a greater input of heat energy than the total chemical energy contained in the dry seaweed. If drying heat is produced from fossil fuel combustion, the resulting seaweed ethanol system would have very poor performance and would likely have an EROI of less than one and a CI higher than that of the input fossil fuel. In contrast to fossil fuel, renewable heat sources, like solar thermal and geothermal, are a potentially viable option for dying seaweed because renewable heat is not included in EROI as an input and because renewable heat sources typically have a very low CI.

Renewable heat systems often require electricity to operate as they use fluid circulation pumps, fan motors, and other support systems. This is included in the model as drying system electricity. The case where electrical input is needed for drying is shown in Figure 4-1 by the transport and drying pathway. Electricity input for renewable drying systems is characterized by the ratio of heat output to electricity input called the *coefficient of performance* (COP). Drying system electricity is calculated from the required water removal in drying, heat requirement per unit water removed, and drying system COP. Construction of the heat collection system has associated indirect energy inputs and GHG emissions, but only electricity input is considered in the model.

4.1.3 Energy input in transport and distribution

If seaweed drying is not required, fresh seaweed is collected from seaweed farms distributed over a large area, consolidated for transport, and sent to the conversion facility. If seaweed drying is required, fresh seaweed is transported to a drying facility, dried, and the resulting dry seaweed is transported to the conversion facility. Using ether wet or dry seaweed, the conversion facility produces anhydrous ethanol that is then denatured on site with a small quantity of gasoline. This denatured ethanol can be transported to specially designed fuel stations for immediate use, or it can be sent to a blending facility, mixed with additional gasoline, and distributed as a blended fuel (e.g. E5, E10, E85) [42]. The energy used to transport the gasoline mixed with denatured ethanol and the gasoline mixed with ethanol blends is not included as an energy input in the model. Seaweed transport and ethanol distribution requires an array of vehicles (boats, barges, trains, trucks, etc) determined by geography, locally available infrastructure, drying heat resource locations (if drying is required), and ethanol plant locations. Transport fuel energy input is calculated from the total distance traveled, mass flow carried, and fuel consumption rate for each required vehicle.

4.1.4 Energy input in conversion

Process fuel and process electricity are the energy inputs required by the conversion facility to convert wet or dry seaweed feedstock into ethanol and co-products. Because seaweed ethanol has only been produced on the experimental scale [4][9][12], data for these process inputs is not available, and so they must be estimated.

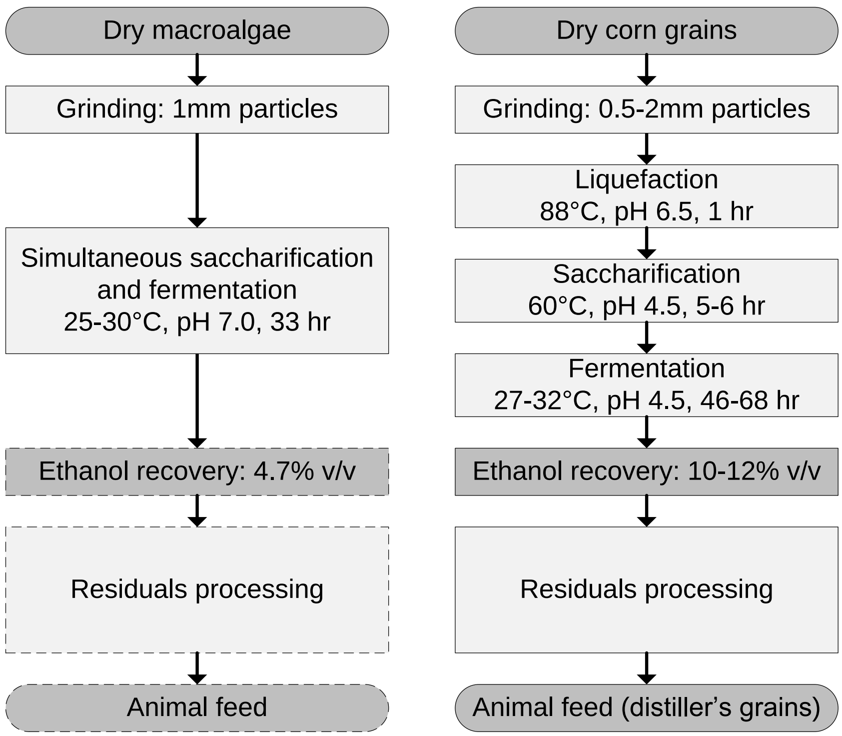


Figure 4-2: Comparison of seaweed conversion, and dry grind corn ethanol conversion. Ethanol concentration is shown in percent by volume and additional steps added in the seaweed conversion model are shown with dashed lines.

The conversion experiment conducted by Wargacki et al. [12] is similar to the dry grind corn ethanol process [35] as shown in Figure 4-2. Based on this similarity, seaweed ethanol production is assumed to require the same basic energy inputs as the dry grind process: boiler fuel to provide heat for saccharifaction, fermentation, and distillation and electricity input for grinding, pumping, and other support operations. Unfermentable seaweed components, like protein and lipids, can be used to produce a variety of co-products including methane, fertilizer, and animal feed [7]. Co-product processing in seaweed ethanol production is assumed to require varying quantities of additional fuel and electricity input depending on the type of co-product produced and quantity of unfermented mass left after ethanol conversion.

Process fuel and process electricity for seaweed ethanol production are simply the sum of fuel and electricity inputs for both ethanol and co-product production. Energy use in co-product production is calculated from the energy use per unit of co-product produced, the fermentable fraction of the seaweed mass processed, and the conversion rate defined below.

Conversion rate is the yield of ethanol per unit of seaweed solids. As discussed in Section 3.3.2, existing estimates for conversion rate are limited to specific seaweed species and do not provide a mechanism to account for variation in seaweed composition, and as discussed in Section 2.2.2, total fermentable fraction (i.e. the sum of alginate, laminarin, and mannitol content) can vary significantly throughout the year, and it can vary with seaweed production location. Values for conversion rate that do not consider these composition variations may be of limited value for assessing ethanol production in specific locations or for ethanol production during specific months of the year. In the model, we propose a conversion rate calculation based on seaweed composition, ideal ethanol yield from each fermentable component, and conversion efficiency for each fermentable component to account for variation in seaweed composition. First, the ethanol yield from each fermentable component is calculated using the ideal ethanol yield for that component, conversion efficiency for that component, and the mass of that component present in the seaweed, and then conversion rate is calculated by summing the ethanol yield from each fermentable component. Ideal ethanol yield is calculated based on the metabolic path used to convert each component into ethanol as shown in Appendix A and conversion efficiency is taken from experiments found in the literature.

4.1.5 GHG emissions

GHG emissions include direct emissions for the seven energy inputs described above and indirect emissions from ethanol vapor loss and fertilizer use. Direct GHG emissions are calculated for each energy input shown in Figure 4-1 using their corresponding carbon intensities. Because transport fuel represents the combustion of an array of transport fuels with potentially different carbon intensities, direct emission for transport is calculated using total distance traveled, mass flow carried, fuel consumption rate, and fuel carbon intensity for each vehicle shown in Figure 4-1. Indirect emission for ethanol vapor loss is calculated using the mass of ethanol vapor lost in distribution and the *global warming potential* (GWP) for ethanol vapor. The mass lost in delivery is assumed to be small; therefore, the ethanol loss has a negligible effect on distribution energy input and direct emissions. Indirect emission for fertilizer use is calculated from the mass of fertilizer applied and an indirect emissions factor. Fertilizer application is discussed further in Section 2.4.1.

4.1.6 Co-product credits

Co-product credits are negative energy inputs or GHG emissions included in the model to account for the reduction in energy use or emissions caused by co-product use. The effect of co-products from conventional ethanol production is typically calculated using the displacement method [16]. Here, ethanol co-products are assumed to displace a quantity of similar conventional products. This is assumed to eliminate the production of that quantity of displaced product, thus reducing energy use and GHG emissions by the amount that would have been required to produce the displaced products. The displacement method is data intensive. It requires knowledge of the specific market where the co-products are used to determine what conventional products are displaced, and it requires knowledge of energy input and GHG emissions for the production of each product displaced. The energy input reduction and the GHG emission reduction achieved per unit of co-product produced are called the *energy co-product credit* and *emissions co-product credit* respectively. In the model, credits per unit of co-product produced must be calculated with additional analysis or taken from the literature. Total co-product credits are calculated from provided energy and emission co-product credit values and the total mass of each co-product produced.

4.2 Near shore ethanol yield

Near shore seaweed farming is the dominant form of seaweed production in the current market (Section 2.3), and it is the most likely seaweed source for ethanol production in the near term. Installing near shore seaweed farming capacity is a complex issue, and it is beyond the scope of this work to calculate the true ethanol yield from near shore seaweed farming, but production potential for a given region is estimated from total available coastline and seaweed production rate from a representative region.

The process of near shore seaweed farming is explained in Section 2.3.1. Seaweed farming potential and thus ethanol production potential depends on the total ocean area available for seaweed farming. Because ocean area suitable for near shore seaweed farming generally lies within a few kilometers of shore, the total area suitable for near shore farming is assumed to be a function of total available coastline. Ethanol production for near shore farming in a region of interest or *near shore ethanol yield* is estimated from total available coastline using the seaweed production rate per unit of coastline from a representative region, and ethanol conversion rate explained in section 4.1.4. Seaweed production rate in the representative region is estimated by dividing total seaweed production from the representative region by the regions total coastline length, and an average seaweed composition and average conversion rate are assumed for all seaweed produced and converted.

4.3 Cost analysis

The model addresses the cost of seaweed ethanol production based on an analysis of the conversion facility. Because seaweed farming cost and seaweed drying cost vary significantly with the species cultivated, farming method, drying method, and region of production, a generally applicable cost analysis of seaweed farming and seaweed drying was outside the scope of this work; therefore, only the cost of the conversion facility is modeled. The cost of constructing and operating a seaweed conversion plant and the revenue from ethanol and co-product sales are used to calculate the maximum price that the conversion facility can pay for dry, delivered feedstock or the *maximum feedstock cost*. This performance metric gives a benchmark to determine if a given seaweed farming and drying system can produce and deliver seaweed at an acceptable cost.

4.4 Model architecture

The model calculates EROI, CI, near shore ethanol yield, and maximum feedstock cost to characterize the performance of any seaweed ethanol production system. These performance metrics are calculated using the energy inputs, GHG emissions, and co-product credits shown in Figure 4-1 and discussed in Sections 4.1 to 4.3 and using the conversion rate discussed in Section 4.1.4 . The four metrics and conversion rate are defined in Sections 4.4.1 to 4.4.5, and the energy inputs, GHG emissions, and co-product credits required for their calculation are detailed in Sections 4.4.6 to 4.4.8.

4.4.1 EROI

$EROI$ for any energy carrier production system is defined from total carrier energy or total useful energy output, E_{out}, and total energy input required for carrier production, E_{input}, as shown in Eq. (1).

$$EROI \equiv \frac{E_{out}}{E_{input}} = \frac{E_{EtOH}}{E_{input} - K_N} \tag{1}$$

E_{input} does not include the primary energy collected that is converted into carrier energy. Examples of primary energy include biomass chemical energy, petroleum chemical energy, solar radiation, and wind kinetic energy. In this model, ethanol is the useful carrier produced and calculation of $EROI$ includes the co-product credits shown in Figure 4-1. E_{EtOH} is total ethanol chemical energy and K_N is total co-product credit for energy input.

Energy inputs and co-product credits in the model are calculated per unit of ethanol higher heating value or as *specific quantities*. Specific energy input, specific GHG emission, specific mass flow, and specific co-product credit are noted with prime notation, X', as shown in Eq. (2).

$$X' \equiv \frac{X}{E_{EtOH}} \tag{2}$$

Where, X is total quantity, and E_{EtOH} is total ethanol chemical energy produced. Specific energy input, specific GHG emission, specific mass flow, and specific co-product credit quantities are denoted as E', G', m', and K' respectively. Total energy input, total GHG emission, total mass flow, and total co-product credit are denoted as E, G, m, and K respectively.

$EROI$ is calculated using specific quantities with Eq. (3).

$$EROI = \frac{1}{\sum_i E_i' - K_N'} \tag{3}$$

Where E_i' are specific energy inputs for the ethanol system and K_N' is the specific co-product credit for energy inputs.

4.4.2 CI

CI for any energy carrier system is defined with Eq. (4)

$$CI \equiv \frac{G_{out}}{E_{out}} \tag{4}$$

Where G_{out} is total GHGs emitted during carrier production.

For seaweed ethanol, CI is measured in *grams of carbon dioxide equivalent* (gCO_2e) per unit of ethanol produced, and it is calculated from the specific direct emissions, indirect emissions, and co-product credits shown in Figure 4-1 using Eq. (5).

$$CI = \sum_i G_i' + \sum_i G_{I,i}' - K_M' \tag{5}$$

Where $G_i^{'}$ are the specific direct emissions associated with direct energy inputs, $G_{I,i}^{'}$ are specific indirect emissions, and $K_M^{'}$ is the total specific co-product credit for emissions.

4.4.3 Conversion rate

Ethanol yield from any mass of fresh brown seaweed, m_{EtOH}, can be calculated from its moisture content and a composition dependent conversion rate, R_C , using Eq. (6).

$$m_{EtOH} = m_{SW}\left(1 - M_f\right)R_C \tag{6}$$

Where m_{SM} is the mass of fresh seaweed and M_f is the seaweed's wet basis moisture content. R_C is the seaweed conversion rate giving the mass of ethanol produced per mass of seaweed solids (i.e. seaweed at 0% moisture) processed at the ethanol conversion facility. Conversion rate is calculated with Eq. (7)

$$R_C = \sum_i \eta_i f_i \psi_i \tag{7}$$

Where $\eta_i$and ψ_i are the conversion efficiency and ideal ethanol yield respectively for each fermentable seaweed component. Eq. (7) is indexed by the eight primary components of brown seaweed shown in Table 4-1.

Table 4-1: Components of brown seaweed

Component[a]	Composition [%][b]	Index[c]
Alginate	23	1
Laminarin	14	2
Mannitol	12	3
Proteins	12	4
Cellulose	6	5
Fucans	5	6
Lipids	2	7
Ash	24	8
Moisture	88	-

Moisture content is given in wet basis, and the remaining component values are given in percentage of total solids. [a] Main components of all brown seaweeds [11]. [b] Typical composition for the Laminaria species [8]. [c] Summation index for Eq. (7), (19), (20), (41), and (42).

Assuming 90% conversion efficiency for mannitol, laminarin, and alginate, using ideal ethanol yield from Table A-1 in Appendix A, and using the composition data provided by Reith et al. in Table 4-1 gives a conversion rate of 0.23 kg per kg of seaweed dry mass which is similar to the conversion rate estimate of 0.254 kg/kg from Roesijadi et al. [7] referencing Reith et al.

4.4.4 Near shore ethanol yield

Near shore ethanol yield for a given section of coastline, Y_X, is calculated using coastline length for the region of interest, L_{CL}, the annual seaweed production in a representative region, P, and seaweed-to-ethanol conversion rate as shown in Eq. (8)

$$Y_X \cong \frac{P\left(1-M_f\right)R_C}{L_{CL}\rho_{EtOH}} L_{CL,X} \tag{8}$$

Where $L_{CL,X}$ is the section of coastline being examined, M_f is the moisture content of fresh seaweed, and R_C is the seaweed conversion rate calculated with Eq. (7).

4.4.5 Maximum feedstock cost

Maximum feedstock cost, C_{SW}, is defined as the maximum price the conversion facility can pay for dry seaweed while still remaining profitable. It is determined using the annual cost of feedstock, C_F, calculated with present worth analysis as shown in Eq. (9).

$$C_F = R - C_{OP} - \frac{C_{CAP}}{\frac{(1+i_{ROR})^{t_{OL}} - 1}{i_{ROR}(1+i_{ROR})^{t_{OL}}}} \tag{9}$$

Where C_{CAP} is the capital cost of the facility in year zero, C_{OP} is the yearly operating cost of the facility less the cost of feedstock, R is annual ethanol and co-product revenue, i_{ROR} is the rate of return, and t_{OL} *is* the operational life of the ethanol plant.

C_{SW} is calculated from the annual cost of feedstock and ethanol plant production capacity, P_{cap}, using Eq. (10).

$$C_{SW} = \frac{C_F \cdot R_C}{P_{cap}\rho_{EtOH}} \tag{10}$$

4.4.6 Energy inputs

Specific sporeling electricity input, $E_{SP}^{'}$, is calculated based on sporeling batch size and tank power requirements as shown in Eq. (11)

$$E_{SE}' = \frac{E_C + E_L + E_P}{R_{SW}\mu} \tag{11}$$

Where E_C, E_L, and E_P are total electricity input per batch of sporelings for cooling, lighting, and circulation pumps respectably, R_{SW} is the rate of fresh seaweed production per batch of sporelings, and μ is the ethanol energy equivalent for fresh seaweed calculated with Eq. (12).

$$\mu = HHV_{EtOH}(1 - M_f)R_C \tag{12}$$

Specific sporeling heating fuel input, $E_{SF}^{'}$, is calculated with Eq. (13).

$$E_{SF}' = \frac{E_H}{R_{SW}\mu} \tag{13}$$

Where, E_H is the total heating fuel input required per batch of sporelings.

Specific boat fuel input, E_{BF}', covers sporeling and seaweed transport, support operations, and boat idling, and it is calculated with Eq. (14).

$$E_{BF}' = (T_{TR} + T_{SO} + T_{IDL})\frac{1}{\mu} \tag{14}$$

Where T_{TR} is total fuel use per unit of fresh seaweed produced for transporting mature seaweed fronds and sporelings, T_{SO} total is fuel use per unit of fresh seaweed for other support operations, and T_{IDL} is total fuel use per unit of fresh seaweed for vehicle idling during production operations.

Specific drying system electricity input, $E_{DE}^{'}$, is calculated from specific water removal, drying heat required, and system COP using Eq. (15).

$$E_{DE}' = \frac{m'_{WR}H}{COP_H} \tag{15}$$

Where H is the drying heat required per unit of water removed from the seaweed, COP_H is the coefficient of performance for the heating technology (e.g. solar thermal or geothermal) used to dry the seaweed, and m'_{WR} is the specific mass flow of water removed in drying calculated with Eq. (16),

$$m'_{WR} = \left(M_f - \frac{M_d\left(1 - M_f\right)}{1 - M_d}\right)\frac{1}{\mu} \tag{16}$$

M_d is the moisture content of dry seaweed.

Specific transport fuel input, $E_{TF}^{'}$, depends on the distance traveled, mass flow, and fuel use rate for each vehicle in the system examined, and it is calculated using Eq. (17).

$$E'_{TF} = \sum_i d_i m'_i F_i \tag{17}$$

Where d_i is the distance traveled by each vehicle, $m_i^{'}$ is the specific mass flow carried by each vehicle, and F_i is the fuel use factor for each vehicle.

Specific process fuel input, $E_{PF}^{'}$, is the sum of fuel use in ethanol production and fuel use in co-product processing calculated with Eq. (18).

$$E'_{PF} = E'_{EF} + \sum_i D'_i E_{CF,i} \tag{18}$$

Where $E_{EF}^{'}$ is specific fuel input for ethanol production, $E_{CF,i}$ is the fuel input for processing co-product i, and $D_i^{'}$ is the specific mass of co-product i produced calculated with Eq. (19)

$$D'_i = D' \frac{\sum_{\mathrm{i}} f_i}{\sum_{\mathrm{j}} f_{\mathrm{j}}} \tag{19}$$

Where f_k is the mass fraction of total seaweed solids for component k, j is the set of all unfermentable components in the seaweed feedstock, i is a subset of j containing the unfermentable seaweed components used to produce co-product i, and D' is the total specific co-product production rate calculated with Eq. (20).

$$D' = \frac{1}{R_C \cdot HHV_{EtOH}} \left(\sum_j f_j \right) \tag{20}$$

Eq. (19) and Eq. (20) are indexed by the eight primary components of brown seaweed shown inTable 4-1.

Specific process electricity input, $E_{PE}^{'}$, is the sum of electricity use in ethanol production and electricity use in co-product processing calculated with Eq. (21).

$$E'_{PE} = E'_{EE} + \sum_i D'_i E_{CE,i} \tag{21}$$

Where E'_{EE} is specific electricity input for ethanol production, and $E_{CE,i}$ is the electricity input for producing co-product i.

4.4.7 GHG emissions

Direct GHG emissions for each energy input, G'_i, are calculated based on the energy consumed, E'_i and its respective carbon intensity I_i using Eq. (22)

$$G'_i = E'_i I_i \tag{22}$$

Note that E'_i must be defined for every energy source with a unique CI.

Transport fuel GHG emission, G'_{TF}, depends on the CI for the each vehicle used, and it is calculated with Eq. (23).

$$G'_{TF} = \sum_i d_i m'_i F_i I_i \tag{23}$$

Fugitive ethanol emissions, $G'_{I,E}$, are calculated from the mass of ethanol lost during ethanol transport as shown in Eq. (24).

$$G'_{I,E} = \frac{m_{EL}}{1 - m_{EL}} \frac{GWP_{EtOH}}{HHV_{EtOH}} \tag{24}$$

Where m_{EL} is the mass of ethanol lost in distribution per mass of ethanol produced, and GWP_{EtOH} is the 100 year global warming potential for ethanol.

Indirect fertilizer emissions, $G'_{I,F}$, are calculated from the quantity of fertilizer applied and a corresponding emission factor as shown in Eq. (25).

$$G'_{I,F} = m_{FR} I_{FR} \frac{1}{\mu} \tag{25}$$

Where m_{FR} is fertilizer applied per unit of fresh seaweed produced and I_{FR} is indirect GHG emission per unit of fertilizer applied.

4.4.8 Co-product credits

Specific energy, $K_N^{'}$, and specific emission, $K_M^{'}$, co-product credits for a general collection of co-products are calculated from the specific mass of each co-product produced and the energy or emission credit achieved by each type co-product produced. They are calculated with Eq. (26) and Eq. (27).

$$K_N' = \sum_i D_i' K_{N,i} \tag{26}$$

$$K_M' = \sum_i D_i' K_{M,i} \tag{27}$$

Where $K_{N,i}$ and $K_{M,i}$ are the energy and emissions credits respectively achieved by co-product i.

4.5 Summary

In this chapter, a general well-to-wheel model was developed for ethanol production from seaweed biomass, covering the processes of seaweed production, drying, seaweed transport, seaweed conversion, and ethanol distribution. A tool was developed to estimate the ethanol yield from any mass of brown seaweed given its composition, and a tool was developed to estimate the ethanol production potential of near shore seaweed farming in a given coastal region. Seaweed drying and storage was included as a possible mechanism to deal with the limited seaweed harvest season. The model calculates the performance of seaweed ethanol based on the four metrics EROI, CI, near shore ethanol yield, and maximum feedstock cost.

In the following chapter, the general model is applied to the specific case of seaweed ethanol production from farmed *Saccharina latissima* in BC, Canada.

5 BC case study

In this chapter, the general seaweed ethanol production model is applied to the specific case of *Saccharina latissima* farming in BC. For clarity, the seaweed ethanol production model described in Chapter 4 is called the *general model*, and the model discussed here is called the *case study model*. BC is an interesting case study for several reasons. It has cold, clean, nutrient rich waters well suited to seaweed production [24], development of a seaweed industry could benefit First Nations communities and remote communities in BC, and BC provides a challenging proving ground for seaweed ethanol production. Seaweed transportation is a challenge because the main market for ethanol is in southern BC in the greater Vancouver area while the best areas for seaweed production are in more northern coastal regions, and year round ethanol production is not possible because of *Saccharina latissima's* limited harvest season as discussed in Section 3.3.

In addition to the four performance metrics in the general model, the case study includes an additional performance metric coving the specific cost of seaweed drying and delivery, and it includes a sensitivity study. The case study discussion follows the same basic format as the seaweed ethanol production model: an overview of simplifications and modeling choices is given in Section 5.1; energy inputs, GHG emissions and co-product credits are discussed in Section 5.2; near shore ethanol yield is discussed in Section 5.3; cost analysis is discussed in Section 5.4; Section 5.5 defines the fifth performance metric and gives calculation details for energy inputs, GHG emissions, co-product credits, and cost; and Section 5.6 outlines the sensitivity study. Input data for the case study is shown in Appendix B.

5.1 Overview

Seaweed production is modeled after the process currently used by Cross [24] for *Saccharina latissima* production in BC. This process requires collection of seaweed spores, land based spore cultivation to produce young seaweed called *sporelings*, delivery of the sporelings to an ocean based farm structure, and ocean based growth into mature seaweed. Collection and delivery is done with small skiff, and no cultivation is required during the ocean growth phase.

Similar to seaweed farming in Southern China [19], fertilizer is not required, as ocean nutrient levels are sufficient for seaweed production in many areas in BC

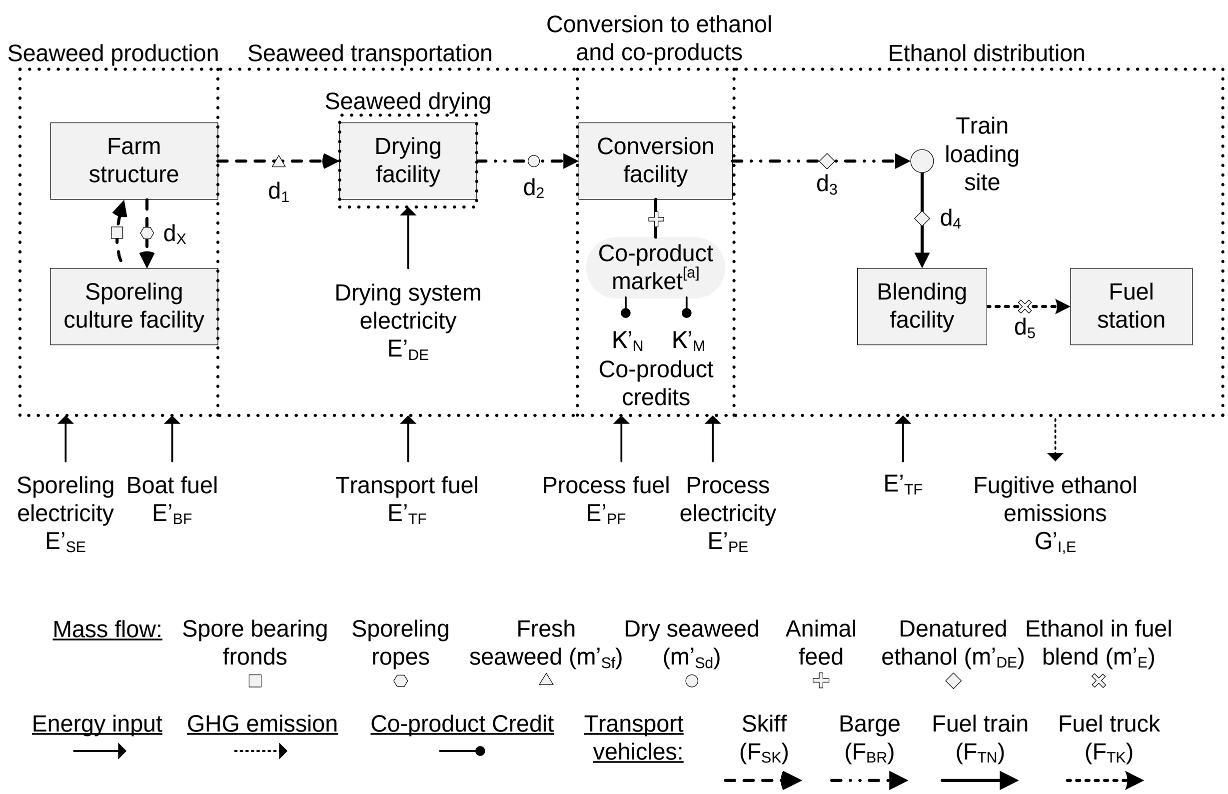


Figure 5-1: Case study of ethanol production in BC. The boundaries of the five processes given in the general model (Figure 4-1) are shown with dotted lines and required facilities are shown with solid lines. Vehicles used for mass transport between each facility are shown with arrows, and the mass type transported by each vehicle is indicated by an icon above each arrow. Transportation distances d_X and d_1 to d_5 are given in Appendix B and illustrated in Figure 5-2 below. Fuel use factors for each vehicle are named in the legend and given in Appendix B. Direct GHG emissions are omitted for clarity. [a] Transportation of animal feed to the co-product market is not included as an input as it is included in the calculation of co-product credits.

A schematic of the case study model is shown in Figure 5-1.The model includes a sporeling culture facility and farm structure that are used for seaweed production, a seaweed drying facility, an ethanol conversion facility, an ethanol blending facility, and a fuel station. Fresh seaweed, dry seaweed, and fuel are transported between these facilities by skiff, barge, train, and truck as indicated in Figure 5-1. Solar thermal drying is used for drying seaweed, and the electricity consumed by fans and other support equipment at the drying facility is supplied by either a renewable energy source or a diesel generator. Dry seaweed is stored at the conversion site and taken out of storage as required. Energy inputs and finances for the seaweed conversion facility are modeled based on the dry grind corn ethanol process and the seaweed conversion experiments found in literature. The residue remaining after ethanol production is converted into animal feed as a co-product, and co-product credits for the feed are calculated assuming the feed it displaces a mix of conventional animal feed and animal mineral supplements.

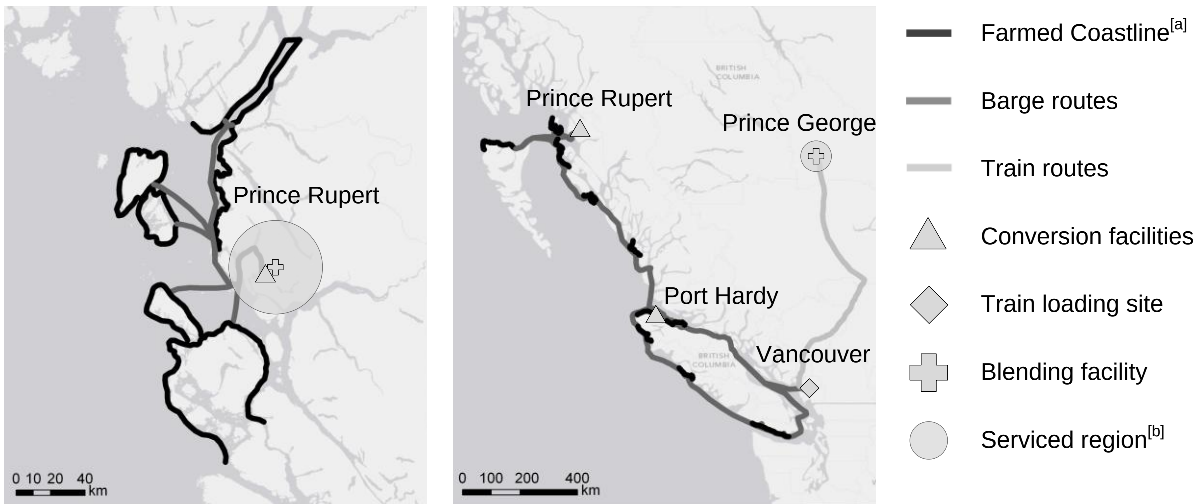
Transport distances for the case study are taken from three transport scenarios shown in Figure 5-2. In the minimum transport scenario, seaweed farming, ethanol production, and ethanol consumption are assumed to occur in a small, local region. In the expected transport scenario, seaweed production occurs over a wide coastal region and ethanol is distributed a significant distance inland, but seaweed is dried before long distance delivery. In the wet transport scenario, the same distances as the expected transport scenario are used, but fresh seaweed is barged directly to the conversion facility and dried near the conversion facility, greatly increasing the transported mass. The case study analysis uses the expected transport scenario, and the minimum and wet scenarios are considered in the sensitivity study.

5.2 Energy inputs, GHG emissions, and co-product credits

The case study model includes six of the seven energy inputs considered in the general model and only one indirect GHG emission source. The energy input for sporeling heating is included with sporeling electricity input, as electric heating is used, and the indirect emission from fertilizer application is not included, as fertilizer is not typically applied in BC. The treatment of the six energy inputs is described below followed by discussion of GHG emissions and of co-product credits.

5.2.1 Energy input in seaweed production

Inputs for seaweed production and the assumed growth characteristics are determined based on the process description in Section 2.4. In this case, a floating farm structure similar to that shown in Figure 2-4B is used for seaweed production, a sporeling culture facility is used to prepare young seaweed for the farm structure, and a skiff is used to move materials from the cultivation facility to the farm, for managing the farm structure, and to collect spore bearing seaweed fronds. Seaweed biomass reaches a maximum towards the end of July and declines in



A) Minimum transport scenario

B) Expected transport scenario and wet transport scenario

Figure 5-2: Transport scenarios. Minimum, expected, and wet transport scenario are considered in the case study and sensitivity study to explore the effect of transportation distance on overall system performance and to examine the effect of transporting wet vs. dry seaweed. Each scenario follows the system schematic shown in Figure 5-1. [a] Regions containing sporeling culture facilities, farm structures, and drying facilities are shown in black, and the distances between these three locations are shown in Table B-6 of Appendix B. Farmed coastline sections in Figure 5-2B follow the distribution of large natural kelp beds found from surveys of BC's natural stocks [43]. [b] Barge routes follow the farmed to access drying facilities and farm sites. [c] The region containing fuel stations serviced by each blending facility is shaded grey. [d] The wet transport scenario uses the transport distances shown in Figure 5-2B, but wet seaweed is barged directly to the conversion facility.

the following months [24]. At this point, a portion of the crop is left to develop spores for producing the next generation of sporelings and the remaining seaweed is harvested manually by collecting the ropes to which the seaweeds are anchored. Harvest is assumed to occur in July and August, defining the harvest season.

Total sporeling electricity use is calculated using the average power draw of the sporeling tank, the time to produce a batch of sporelings, and seaweed production per batch, and total boat fuel use is calculated from the total distance traveled by the skiff and skiff idling time during the collection of mature fronds, installation of seedlings, and harvesting of seaweed. Sporeling electricity use and boat fuel use per unit of ethanol produced are calculating using the conversion rate for *Saccharin latissima* collected during the July-August harvest season. As the harvest season occurs during the seaweeds period of maximum biomass content, the composition for *Saccharina latissima* in BC during the harvest season is approximated by the composition of Scottish *Saccharina latissima* for its period of maximum biomass in September-October as shown in Figure 2-2.

5.2.2 Energy input in drying

All solar thermal drying systems follow the same basic principle of operation. Solar radiation is used to heat air to lower the air's relative humidity, the warm dry air is passed over the product to be dried, moisture transfers from the product to the warm air, and the now humid air is rejected to the atmosphere. Heating and circulation of air can be accomplished in many different ways, and solar thermal drying systems can take a variety of forms [44] from natural convection based systems driven only by solar energy [45] to complex systems using fans, heat pumps, and thermal storage that offer increased drying rate at the cost of electricity input [46].

A forced convection system with an electric blower is considered in the case study, and a heat pump driven system with thermal storage is considered in the sensitivity study. The solar thermal drying facility is powered by a low emission source of electricity in the case study and by a diesel generator in the sensitivity study. Drying system electricity input is calculated from the required water removal during drying, the heat requirement per unit water removed, and the drying system COP as described in the general model.

5.2.3 Energy input in transport and distribution

Transport fuel is calculated using the transportation and distribution pathway shown in Figure 5-1 and distances from the expected transportation scenario shown in Figure 5-2B. Fresh seaweed is transported from the farm structure to a nearby drying facility with a small skiff, dried, and barged to the conversion facility for storage and conversion to ethanol. Denatured ethanol (97% by volume [16]) is transported from the conversion facility by barge and train to a blending facility where it is combined with additional gasoline to produce a 5% by volume ethanol/gasoline blend (E5). This fuel blend is finally trucked to fuel stations for transfer to vehicle fuel tanks and final use.

Transport fuel energy input is calculated from the total distance traveled, mass carried, and fuel consumption rate for each required vehicle. As in the general model, the addition mass from gasoline in denatured and blended ethanol is not included. The energy input needed to transport co-products from the conversion facility to their point of use is not included in transport fuel, as the energy input and GHG emission from co-product transport are accounted for in the data from Bremer et al. [16] used to calculate co-product credits.

5.2.4 Energy input in conversion

Process fuel and electricity for ethanol production are approximated using data from commercial dry grind corn ethanol plants, and fuel and electricity use in co-product production are calculated assuming that animal feed is the only co-product. As shown in Figure 4-2, the seaweed fermentation process used by Wargacki et al. is similar to the standard process of dry grind corn ethanol production; however, the concentration of ethanol achieved during fermentation is significantly lower for seaweed ethanol. As lower concentration increases the energy required for distillation, process fuel for ethanol production is calculated using the fuel use for dry grind ethanol production and an ethanol production fuel scaling factor. The dry grind process typically achieves a concentration of 10-12% ethanol by volume [35], but the Wargacki et al. process only achieves an ethanol concentration of 4.7% by volume [12] which would double the energy needed in distillation per unit of ethanol distilled relative to dry grind[47]. The case study assumes a future case where seaweed fermentation processes can achieve the same ethanol concentration as a typical dry grind process, and the sensitivity study considers distillation from 4.7% by volume. Electricity input for ethanol conversion is assumed equal to electricity input for the dry grind process.

Fuel and electricity use in co-product production are calculated assuming animal feed as the only co-product and assuming the same feed production process used in dry grind corn ethanol production. The unfermented residue left from seaweed conversion is compared to corn distiller’s grains as shown in Table 5-1.

Table 5-1: Comparison of corn distiller's grains to seaweed distillation residue

Solids mass fraction	Corn distiller's grains with solubles [48]	Seaweed distillation residue [a] (non-ash portion)	Seaweed distillation residue [a] (whole product)
Ash	5.8% [49]	0%	56%
Protein	25-32%	36%	16%
Fiber	40-44%	32%[b]	14%[b]
Fat	8-10%	11%[c]	4.9% [c]

[a] Unfermentable components of *Saccharina latissima* from Black [6] September 1947 inlet sample. [b] Cellulose content for *Saccharina latissima* from Black [20] September 1946 inlet sample. [c] Assuming a 2% lipid content in fresh seaweed.

As seaweed residue is similar to corn distiller's grains and raw seaweed can be used as animal feed [14], the unfermentable component of seaweed feedstock is assumed to be viable as animal feed. In the dry grind process, distillation residue is processed to produce a variety of animal feed products called distiller's grains. The three main types of distiller's grains produced are *wet distiller's grains with solubles* (WDGS), *modified distiller's grains with solubles* (MDGS), and *dried distiller's grains with solubles* (DDGS) [16]. To produce these products, distillation residue is first centrifuged, leaving solids rich *wet distiller's grains* and water with soluble nutrients called *thin stillage*. A portion of the thin stillage is fed back to the fermentation process and the remainder is passed through an evaporator to supply water for distillation steam. The concentrated stillage leaving the evaporator is mixed wet distiller's grains to produce WDGS and this mixture is dried in a rotary drum drier to produce either MDGS or DDGS [35]. WDGS is typically 65% moisture, MDGS are dried to 55% moisture, and DDGS are dried to 10% moisture. It is assumed that seaweed ethanol distillation residue is processed into *wet feed*, *modified feed*, and *dry feed* using the same process as WDGS, MDGS, and DDGS production respectively.

The three seaweed feeds are produced in the same ratio as wet/modified/dry distiller's grains produced by the collection of US dry grind plants surveyed by Bremer et al. [16], and the extremes of 100% wet feed and 100% dry feed are considered in the sensitivity study. Process fuel input for co-product production is calculated from the non-fermentable fraction of seaweed solids, conversion rate as discussed in the general model, the mass fraction of each type of feed produced, and the natural gas input for drying each type of feed in the dry grind process. As direct data on electricity use in dry grind feed production was not available and because seaweed ethanol production produces more feed per unit of ethanol than dry grind ethanol production, the electricity input for co-product processing is calculated by scaling the electricity input for distiller's grain production in the dry grind process by an animal feed production scaling factor to account for the additional mass of animal feed processed in seaweed conversion.

For calculating conversion rate, seaweed composition is assumed equal to that of Scottish *Saccharina latissima* in September-October as described in Section 5.2.1 and shown in Figure 2-2. The ideal ethanol yield for alginate, laminarin, and mannitol were calculated assuming 100% of the input alginate, laminarin, and mannitol was converted to ethanol using the metabolic processes described by Wargacki et al. [12] for conversion of alginate and Horn [9] for the conversion of laminarin and mannitol. Additional detail is shown in Appendix A. Equal conversion efficiency is assumed for all three fermentable components. Wargacki et al. [12] achieved 80% conversion efficiency for a combination of alginate, laminarin, and mannitol where 90-94% conversion efficiency is typically achieved for corn ethanol [35]. The case study model assumes a future case for seaweed ethanol production with 90% conversion efficiency, but 70% to 94% conversion efficiency is considered in the sensitivity study.

5.2.5 GHG emissions

Direct emissions for all inputs are calculated using the six energy inputs shown in Figure 5-1, transport fuel direct emissions are calculated from the total distance traveled, mass flow carried, fuel consumption rate, and fuel carbon intensity of each required vehicle shown in Figure 5-1, and indirect emissions from ethanol vapor loss are calculated from the mass of vapor lost and ethanol vapor GWP. Indirect emissions from fertilizer application are not included as the seaweed production system discussed in Section 5.2.1 does not require fertilizer.

5.2.6 Co-product credits

Co-product credits are calculated assuming that seaweed animal feed replaces a mix of animal feed and animal mineral supplements. Because seaweed distillation residue has a significant ash content, seaweed animal feed is considered to be a mix of pure ash called the *ash portion* and a mix of other components called the *non-ash portion*. As seaweed ash contains valuable macrominerals and trace elements [14] [15], co-product credits are calculated assuming that the ash portion replaces animal mineral supplements, and as the non-ash portion is comparable to corn distiller's grains, the non-ash portion is assumed to replace animal feed. The product produced at the ethanol plant can be considered an animal feed premixed with mineral supplements because mineral supplements are often mixed with feed rations before livestock are fed. Energy and emission co-product credit for the non-ash portion are calculated assuming that this portion of the seaweed feed will displace the same feed displaced by corn distiller's grains and thus achieve similar credits. Credits for the ash portion are assumed to be zero as data for displacing mineral supplements was not available. Energy and emission co-product credits equal to those achieved by corn distiller's grains are considered for the ash portion in the sensitivity study.

5.3 Near shore ethanol yield

Near shore ethanol yield is estimated for BC and for the total global coastline using China as a representative region. China is the world's largest producer of seaweed, accounting for 72% of global production [7] while possessing only 4% of global coastline. For both BC and the world coastline, the average fermentable fraction and dry solids content of the seaweed produced is assumed to be equal to that of the *Saccharina latissima* sampled by Black [6] for September 1947 as shown in Figure 2-2, and the average conversion rate is calculated as described Section 5.2.4.

In estimating the near shore yield of the entire world coastline, the productivity of China may be lower than the true seaweed production rate in more tropical areas that can produce multiple harvests per year [14], which would give an underestimate of global yield. However, 45% of world coastline lies in the Canadian and Russian Arctic where seaweed production potential is likely lower than that of China despite the subarctic showing some production potential [50], which may lead to an overestimate of global near shore ethanol yield.

5.4 Cost analysis

Because a true accounting of cost for large scale seaweed ethanol production would require a full process design outside the scope of this work, annual revenue, capital cost, and operating cost are approximated using cost data for the dry grind corn ethanol process. Annual revenue is calculated using the price of raw seaweed animal feed as an approximation for the price of seaweed animal feed and using the wholesale price of gasoline as an approximation for ethanol price. Based the similarity to the dry grind ethanol process discussed in the general model and shown in Figure 4-2, the cost of seaweed ethanol production is approximated by scaling the capital and operating cost of dry grind animal feed processing by the higher feed production rate of seaweed ethanol, by adding the capital cost of onsite feedstock storage, and by removing the cost of saccharifaction. The capital cost of animal feed processing equipment is scaled by the animal feed production scaling factor described in Section 5.2.4.

The energy input cost for both natural gas input and electricity input in animal feed processing is scaled by the percentage increase in natural gas consumption because data was only available for combined natural gas and electricity cost. The percentage increase in natural gas consumption and the percentage increase in electricity consumption due to increased co-product production were 34% and 37% respectively. Because natural gas use accounts for the majority of energy input, the error in scaling only by natural gas use was considered acceptable, and a +/-50% variation of total energy input cost was considered in the sensitivity study.

The capital cost of feedstock storage is calculated assuming the seaweed ethanol facility includes enough storage capacity for an entire year of ethanol production. Corn ethanol plants purchase grain in small batches from grain storage companies and only store enough grain on site for 8-12 days of operation [35]; however, offsite storage services for seaweed are not available in BC. The capital cost of seaweed storage is assumed to be similar to that of corn grain storage. The capital cost of saccharifaction is ignored as the Wargacki et al. process uses simultaneous saccharifaction and fermentation. Remaining capital and operating costs are taken directly from the dry grind ethanol process and all capital and operating costs are converted into 2012 Canadian dollars.

5.5 Case study architecture

The case study model calculates the four performance metrics defined in the general model and an additional performance metric called maximum drying and delivery cost. The five metrics are calculated using the energy inputs, GHG emissions, and co-product credits, near shore production scenarios, and the cost scenario discussed in Sections 5.2 to 5.4. EROI, CI, near shore ethanol yield, and maximum feedstock cost, are defined in Sections 4.4.1 to 4.4.5. Maximum drying and delivery cost is defined below followed by a four section treatment of the energy inputs, GHG emissions, co-product credits, and cost inputs required to calculate each performance metric.

5.5.1 Maximum drying and delivery cost

Maximum drying and delivery cost is a simple extension of maximum feedstock cost defined to highlight the cost of seaweed drying and delivery. Estimates for seaweed production cost are typical given as the cost of fresh, undelivered seaweed, or *fresh cost*, and they do not include the cost of drying seaweed or delivering it to point of use. As the cost of solar thermal seaweed drying was not available and because calculation of delivery cost was outside the scope of this work, maximum drying and delivery cost, C_{DD}, is calculated as a benchmark for combined drying and delivery systems using Eq. (28).

$$C_{DD} = C_{SW} - C_{FSW} \tag{28}$$

Where C_{SW} is maximum feedstock cost defined in Section 4.4.5 and C_{FSW} is the cost of producing fresh seaweed.

5.5.2 Energy inputs

Specific sporeling electricity input, E'_{SE}, is calculated with Eq. (29),

$$E'_{SE} = P_T \frac{t_C}{L_T R_P \mu} \tag{29}$$

Where P_T is the average electrical power draw of the sporeling culture tank (electrical heat, lighting, and pumping), L_T is the length of horizontal farm rope of seeded by each sporeling batch, R_P is the production rate of fresh seaweed per unit of farm rope and t_C is the time required to culture one batch of sporelings, and μ is the ethanol energy equivalent for fresh seaweed calculated with Eq. (12). μ is a function of seaweed conversion rate, R_C, which is calculated with Eq. (7).

Specific boat fuel input, E'_{BF}, is calculated with Eq. (30).

$$E'_{BF} = (2d_X F_{SC} n_{G+I} + F_{SI} t_{IDL}) \frac{HHV_{V,BF}}{R_P \mu} \tag{30}$$

Where d_X is the distance from the sporeling culture facility to the farm site shown in Figure 5-1, F_{SC} is the average fuel use of the planting skiff at cruising speed, F_{SI} is the average fuel use of the planting skiff while idling, n_{G+I} is the number of return trips made between the support site and the farm per meter of planted rope for gathering mature fronds and installing seedlings calculated with Eq. (31), $HHV_{BF,V}$ is higher heating value for boat fuel per unit volume, and t_{IDL} is the total time spend idling calculated with Eq. (32).

$$n_{G+I} = \frac{1}{n_B L_T} + \frac{t_{INST}}{t_{WD}} \tag{31}$$

Where n_B is the number of sporeling batches that can be seeded from one mature frond collection trip, t_{INST} is the time to required to install a meter of sporeling twine onto the farm structure, and t_{WD} is the time spent installing sporelings per boat trip (the work day).

$$t_{IDL} = t_{INST} + \frac{t_{FC}}{L_T} + t_{HARV} \tag{32}$$

Where t_{FC} is the idling time to required to collect a batch of spore bearing fronds and t_{HARV} is the idling time required to harvest seaweed from one meter of horizontal growth rope

Specific drying system electricity input, E'_{DE}, is calculated with Eq. (15), and specific transport fuel input, E'_{TF}, is calculated using Eq. (17) using the mass flow of fresh seaweed, dry seaweed, and ethanol and using travel distances and fuel use rates from Appendix B. The mass flow of fresh seaweed, m'_{Sf}, and dry seaweed, m'_{Sd} are calculated with Eq. (33) and Eq. (34).

$$m'_{Sf} = \frac{1}{\mu} \tag{33}$$

$$m'_{Sd} = \frac{1}{\mu}\frac{\left(1 - M_f\right)}{(1 - M_d)} \tag{34}$$

As in the general model, M_f and M_d are fresh seaweed moisture content and dry seaweed moisture content respectively.

The specific mass flow of pure ethanol within the denatured ethanol, m'_{DE}, and within the fuel blend, m'_{BE} is calculated using, and Eq. (35).

$$m'_{DE} = m'_{BE} = \frac{1}{HHV_{EtOH}} \tag{35}$$

Specific process fuel input, E'_{PF}, is a function of both distillation fuel input and animal feed production fuel input as shown in Eq. (36).

$$E'_{PF} = E_{EF,C}\,\delta_{EF}\,\frac{1}{HHV_{V,EtOH}} + D'\sum_{i=1}^{3} f_{C,i}E_{CF,i} \tag{36}$$

Where $E_{EF,C}$ is natural gas use for ethanol production in the dry grind process, δ_{EF} is the ethanol production fuel scaling factor used to include the effect of low ethanol concentration, $f_{C,i}$ is the mass fraction of each co-product produced, and $E_{CF,i}$ is the natural gas input required for drying each type of animal feed. i = {WF, MF, DF} for wet feed, modified feed, and dry feed respectively. D' is calculated with Eq. (20).

Specific process electricity input, E'_{PE}, is calculated using the electricity use of the dry grind process as shown in Eq. (37).

$$E'_{PE} = E_{EE,C}(A \cdot \delta_{AF} + 1 - \mathrm{A})\,\frac{1}{HHV_{V,EtOH}} \tag{37}$$

Where $E_{EE,C}$ is the electricity in dry grind ethanol production including typical co-product processing, A is the fraction of dry grind electricity input accounted to animal feed processing, and δ_{AF} is the animal feed production scaling factor calculated with Eq. (38).

$$\delta_{AF} = \frac{D' \cdot HHV_{V,EtOH}}{D_{corn}} \tag{38}$$

Where D_{corn} is the animal feed production rate for the dry grind process.

5.5.3 GHG emissions

Specific direct emissions for all specific energy inputs are calculated using Eq. (22), specific transport fuel GHG emissions, G'_{TF}, are calculated using Eq. (23), and specific indirect GHG emissions from ethanol vapor, $G'_{I,E}$, are calculated with Eq. (24). Indirect GHG emissions from fertilizer application, $G'_{I,F}$, are not included as no fertilizer is applied.

5.5.4 Co-product credits

Specific co-product credits for energy, $K_N^{'}$, and emissions, $K_M^{'}$, are calculated with Eq. (39) and Eq. (40).

$$K_N' = D_F' K_{N,F} + D_R' K_{N,R} \tag{39}$$

$$K_M' = D_F' K_{M,F} + D_R' K_{M,R} \tag{40}$$

Where $K_{N,F}$ and $K_{M,F}$ are the energy and emissions credit for corn distiller's grains respectively, $K_{M,R}$ and $K_{M,R}$ are the energy and emissions credit for animal mineral supplements respectively, $D_F^{'}$ is the specific mass of seaweed residue that is similar to animal feed found with Eq. (41), and $D_R^{'}$ is the specific mass of seaweed residue that is similar to mineral supplements found with Eq. (42)

$$D_R' = D' \frac{f_8}{\sum_{i=4}^{8} f_i} \tag{41}$$

$$D_F' = D' \frac{\sum_{i=4}^{7} f_i}{\sum_{i=4}^{8} f_i} \tag{42}$$

Eq. (41) and Eq. (42) are indexed by the eight primary components of brown seaweed shown in Table 4-1.

5.5.5 Cost inputs

Annual revenue, R, is calculated with Eq. (43).

$$R = P_{cap} W_{EtOH} + P_{cap} D' W_{GR} HHV_{V,EtOH} \tag{43}$$

Where W_{EtOH} is the wholesale price of ethanol, W_{GR} is the price of seaweed animal feed, and P_{cap} is the ethanol plant production capacity as defined in the general model.

Capital cost, C_{CAP}, is calculated using Eq. (44).

$$C_{CAP} = S_{FH} + S_{Fr} + S_{Ds} + S_{AF}\delta_{AF} + S_{SLO} + S_{St} + S_{WT} + S_{AC} \tag{44}$$

Where S_{FH}, S_{Fr}, S_{Ds}, S_{AF}, S_{SLO}, S_{WT}, and S_{AC} are the capital costs for feedstock handling, fermentation, distillation, animal feed production, storage and load out, wastewater treatment, and air compression respectively, and S_{St} is the capital cost of the seaweed storage system, calculated with Eq. (45).

$$S_{St} = C_{Sl} P_{cap} \rho_{EtOH} \frac{1}{R_C B(1 - M_d)} \quad (45)$$

Where C_{Sl} is the cost per unit of silo capacity, and B is the bulk density of dry seaweed.

Annual operating cost, C_{OP}, is calculated with Eq. (46)

$$C_{OP} = O_{RM} + O_{Dn} + O_{EI}\delta_{EI} + O_{LSO} \quad (46)$$

Where O_{RM}, O_{Dn}, O_{EI} and O_{LSO} are the annual operating costs for raw materials, denaturant, energy input, and labor/supplies/overhead respectively, and δ_{EI} is the energy input scaling factor calculated with Eq. (47).

$$\delta_{EI} = \frac{E'_{PF} \cdot HHV_{EtOH}}{E_{EF,C} + E_{CF,D}} \quad (47)$$

Where $E_{CF,D}$ is natural gas use in distiller's grain production for the dry grind process.

The conversion between 1999 US dollars and 2012 Canadian dollars is given by equation Eq. (48).

$$C = C_{1999\ USD} R_{EX} N_F \quad (48)$$

Where C is capital or operating cost in 2012 Canadian dollars, $C_{1999\ USD}$ is capital or operating cost in 1999 US dollars, R_{EX} is the CAD to USD exchange rate, and N_F is the 1999 to 2012 US inflation correction factor.

5.6 Sensitivity study

All inputs to the model were individually varied by +/- 50% to determine their effect on the three performance metrics EROI, CI and maximum feedstock cost. Any input that produced less than a +/-5% variation in all three performance metrics was discarded. Individual expected ranges were determined for all the remaining inputs, and the sensitivity study was run again to measure the effect of each expected range on the three metrics. Energy use data for the dry grind corn ethanol process was considered sufficiently certain and was not included in the study. Unless otherwise defined, all cases considered in the sensitivity study are for composition equal to the inlet location sample of *Saccharina latissima* in Sept 1947 from Figure 2-2.

To give a more meaningful result, the effect of transportation system layout and the effect of seaweed composition were examined through the simultaneous variation of multiple inputs. In the case of transportation system layout, the distances d_1 to d_5 shown Figure 5-1 are varied together according to the minimum transport scenario and wet transport scenario shown in Figure 5-2A and Figure 5-2B respectively. In the wet scenario, d_2 to d_5 are the same as in expected scenario, but seaweed is not dried and $m_{sf}^{'}$ is transported over both d_1 and d_2.

In the case of seaweed composition, three separate composition sensitivity studies are considered. In each study, the case study model is run multiple times, the EROI, CI, and maximum feedstock cost are recorded for each run, the run results are sorted, and the maximum and minimum values for EROI, CI, and maximum feedstock cost are recorded as the extremes of the given sensitivity study. In each run, the dry weight mass factions of alginate, laminarin, and mannitol and fresh seaweed moisture content are varied to match the *Saccharina latissima* composition given by Black [6] and described in Section 2.2.1 for a given month and location (E.g. September 1947, inlet location). In the monthly composition study, the case study model is run for each month of composition data given for the inlet location for 1947. In the seaweed farm location study, the model is run for the Sept 1947 open sea composition to show how farm location can affect the three metrics, and in the seaweed production year study, the model is run for the Sept 1948 composition show how production year can affect the three metrics. Aside from transport scenario, monthly composition variation, seaweed farm location, and seaweed production year, all other sensitive inputs are varied individually by the ranges shown in Appendix B

5.7 Summary

This chapter discussed the case of ethanol production from *Saccharina latissima* in BC. Ethanol system performance was analyzed using case study specific choices and simplifications applied to the general model from Chapter 4. Seaweed farming was modeled after the production process used by Cross [24] for *Saccharina latissima* production in BC. Solar thermal drying was chosen to deal with the need for seaweed drying and storage. Additional feedstock storage was included to compensate for lack of a seaweed storage network in BC. Energy input and cost for the ethanol conversion plant were both estimated using data for the dry grind ethanol process and a comparison between the dry grind process and the seaweed conversion processes used by Wargacki et al. [51], and three transportation system configurations were defined. Animal feed was assumed to be a viable co-product due to seaweeds current use as animal feed and the similarity between seaweed ethanol distillation residue and corn ethanol co-product feed. Animal feed production energy input and production cost were modeled based on corn ethanol animal feed production, and co-product credits were calculated assuming that seaweed animal feed displaces a mix of mineral supplements and conventional animal feed

The following chapter presents results from the case study model, giving EROI, CI, near shore ethanol production potential, maximum feedstock cost, and maximum drying and delivery cost for BC, and giving the near shore ethanol production potential of the world coastline. It also includes a simple calculation of animal feed market size.

6 Results

This chapter presents results from the BC case study calculated using data form Appendix B. The chapter is divided into four main sections: the first three cover EROI, CI, and near shore ethanol yield, and the fourth section covers maximum feedstock cost and maximum drying and delivery cost. It also includes a section for the sensitivity study and a section addressing the market for seaweed animal feed. Because animal feed drying energy, animal feed co-product credits, and ethanol plant energy carbon intensity resulted in significantly more variation in EROI, CI, and maximum feedstock compared the other inputs considered in the sensitivity study, the variation caused by these four inputs is presented with the main results in the first four sections. The results for EROI, CI, and near shore ethanol yield are presented in Sections 6.1, 6.2, and 6.3 respectively; maximum feedstock cost and maximum drying and delivery cost are presented in Section 6.4; the sensitivity study is presented in Section 6.5, and animal feed market size is addressed in Section 6.6.

6.1 EROI

Shown in Figure 6-1, seaweed ethanol has an EROI of 1.78 which is slightly higher than the EROI of corn ethanol. Varying the feed production mix from 100% dry feed to 100% wet feed and varying the energy co-product credit from zero to the maximum level calculated by Bremer et al. [16] gives a minimum EROI of 1.33 and a maximum EROI of over 200. This extremely high EROI value indicates that the total energy co-product credit is nearly equal to the total energy input required for ethanol and co-product production.

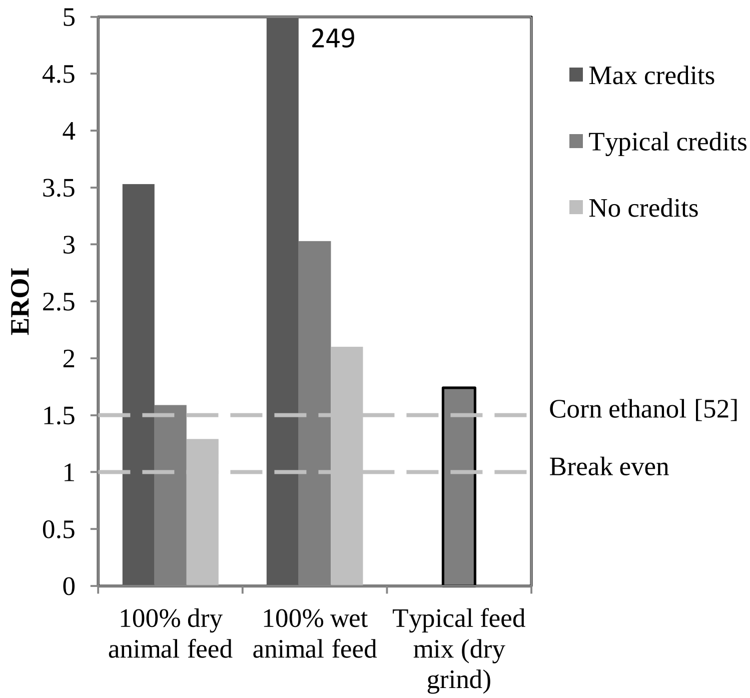


Figure 6-1: EROI of seaweed ethanol considering feed production and co-product credits. EROI varies with the energy input required to dry animal feed and with the energy input co-product credits assumed for the animal feed.

6.2 CI

Shown in Figure 6-2, seaweed ethanol has a CI of 10.1 $gCO_2e\cdot MJ^{-1}$, lower than the CI of all conventional ethanol sources shown. Varying the feed production mix and the varying the emissions co-product credit gives a maximum CI of 32.9 $gCO_2e\cdot MJ^{-1}$ and a minimum CI of -42.4 $gCO_2e\cdot MJ^{-1}$. The maximum CI is still lower than all conventional ethanol sources shown. If coal is used for process fuel and if coal fired generation is used for process electricity, CI ranges from 37.8 to 65.3 $gCO_2e\cdot MJ^{-1}$and is lower than the CI of corn ethanol produced with coal for the full range considered.

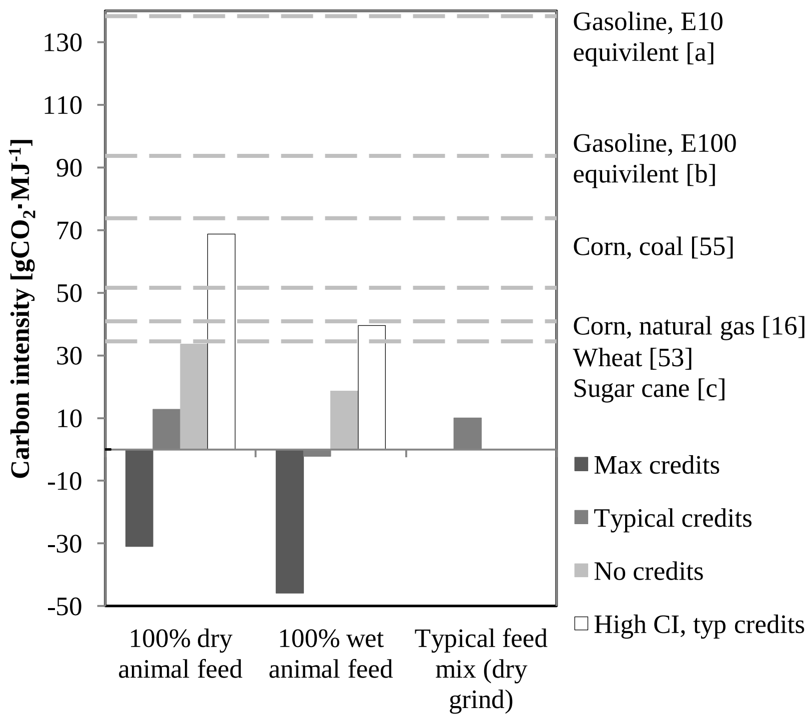


Figure 6-2: CI of seaweed ethanol considering feed production and co-product credits. The first three co-product credit cases consider natural gas as the fuel for both ethanol production and animal feed drying and the high CI case considers coal as heating fuel and coal based electricity input. [a],[b] The top comparison lines represent the specific GHG emissions eliminated by replacing 1L of gasoline with 1L of ethanol in an E10 fuel blend and as E100 respectively. Emission reduction is calculated using the CI of gasoline in BC [53] and the equivalence ration X given by Macedo et al. [54]. X = 1.0 for ethanol blends upto E10, X = 0.75 for neat ethanol (E100). $CI_{EtOH\ Eq} = \frac{HHV_{Gas}}{HHV_{EtOH}} X * CI_{Gas}$. This accounts for both lower energy content of ethanol and the improvement in combustion efficiency achieved with ethanol fuel blends. [c] Domestic use of sugarcane ethanol is approximated by replacing transportation emissions for delivery from Brazil to Canada with domestic delivery emissions for Canadian corn ethanol [53].

6.3 Near shore ethanol yield

Near shore ethanol yield for BC is approximately 1.3 billion liters per year. Processing this volume of ethanol would require 7 ethanol plants with a typical production capacity of 200 $ML \cdot yr^{-1}$ [56]. For comparison, current ethanol consumption in BC is 240 million liters per year, as required to meet the mandatory 5% ethanol content in all gasoline consumed in BC. Near shore ethanol yield for the entire global coastline is approximately 18.4 billion liters per year, and would require 90 typical ethanol plants. As shown in Figure 6-3, global near shore yield is an order of magnitude lower than current global ethanol production and two orders of magnitude lower than global gasoline production.

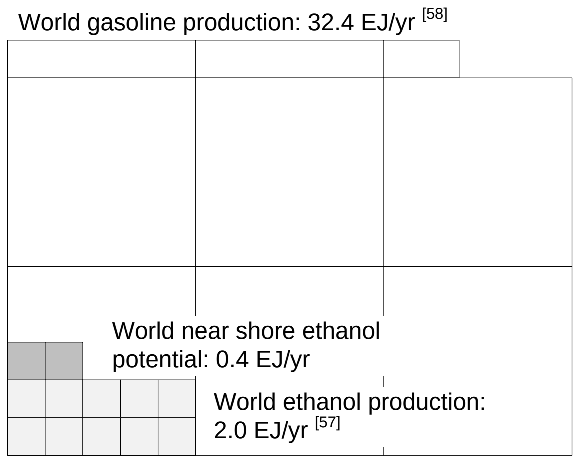


Figure 6-3: Global near shore ethanol yield compared to current world ethanol production. Near shore seaweed farming could significantly increase global ethanol production, but it is likely that open ocean seaweed farming would be required for seaweed ethanol to replace more than a few percent of global gasoline consumption.

6.4 Max feedstock cost and maximum drying and delivery cost

Maximum feedstock cost is shown in Figure 6-4 along with fresh cost values from the literature. Maximum cost is $743 per tonne for the case study and it ranges from $188 per tonne for zero co-product revenue to $987 per tonne for maximum co-product revenue. Maximum feedstock cost is lower than the fresh cost of current BC farming methods and lower than the high end cost of offshore seaweed farming for zero co-product revenue, but it is higher than fresh cost in all other cases.

Maximum drying and delivery cost is shown in Figure 6-5. It is negative for all cases considering the current fresh cost of seaweed production in BC, it is negative for the high end fresh cost for offshore farming combined with zero co-product revenue, and it is positive for all other cases. Maximum drying and delivery cost ranges from $223 to $965 per tonne of dry seaweed if co-product revenue is considered and from $46 to $166 dollars per tonne for the positive cases with zero co-produce revenue.

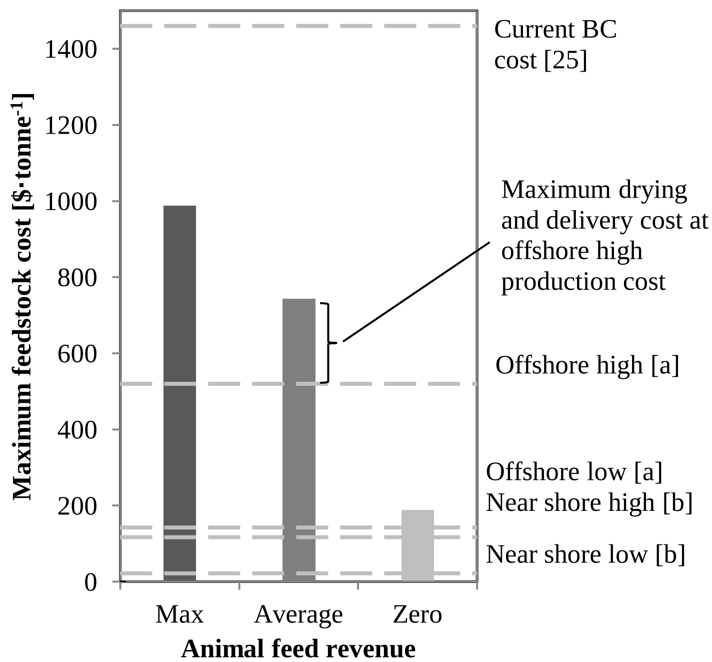


Figure 6-4: Maximum feedstock cost compared to fresh feedstock cost. Price of fresh seaweed is shown with dashed lines. [a] Bruton et al. [5] citing Chynoweth [13]. [b] Roesijadi et al. [7]. Production cost is adjusted for inflation and converted to Canadian dollars [59][60].

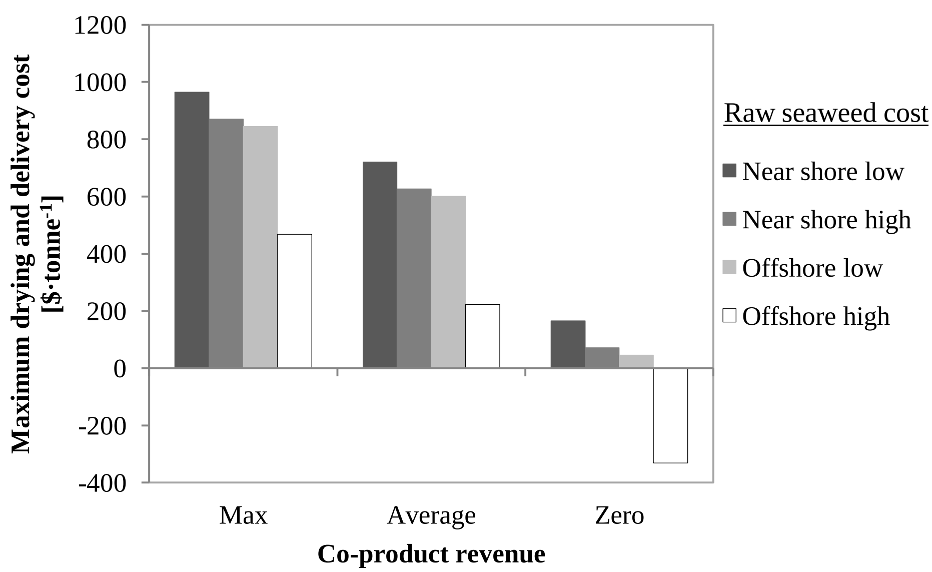


Figure 6-5: Maximum drying and delivery cost for dry seaweed. The maximum cost for solar thermal drying and boat/barge delivery of one unit of dry seaweed feedstock is most significantly affected by the revenue from animal feed sales and by the cost of fresh seaweed production. Maximum drying and delivery cost is calculated using Eq. (28) and data from Figure 6-4.

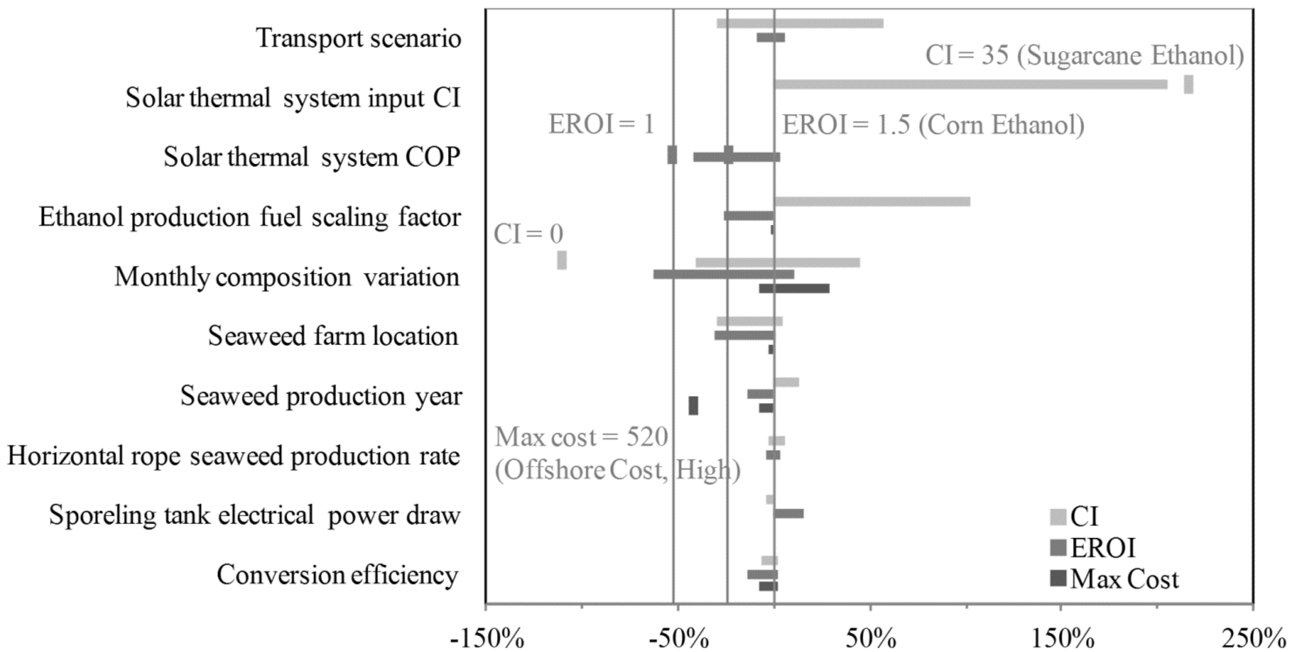


Figure 6-6: Sensitivity study results. Transport scenario, seaweed composition, seaweed farm location, and seaweed production year indicate simultaneous variation in multiple inputs as explained in Section 5.6. Comparison values for corn ethanol EROI, sugarcane ethanol CI, and offshore seaweed production cost are taken from Figure 6-1, Figure 6-2, and Figure 6-4 respectively.

6.5 Sensitivity Study

The sensitivity study results are shown in Figure 6-6 along with EROI, CI, and maximum feedstock cost values for comparison. EROI shows the most significant variation of the three performance metrics. It is most affected by solar thermal system COP and seaweed composition, dropping below 1 for both inputs. Farm location, production year, ethanol production fuel scaling factor, and conversion efficiency each produce an EROI that is less than or equal to that of corn ethanol, but greater than 1. Transport scaling factor and horizontal rope seaweed production rate both decrease EROI but not below that of corn ethanol. Sporeling tank electrical power draw increases EROI to 2.0. CI shows the largest relative variation of the three outputs, but the absolute value of CI remains below that of all current ethanol sources. Solar thermal system input CI and ethanol production fuel scaling factor have the largest relative effect, increasing CI by 21 $gCO_2e \cdot MJ^{-1}$ and 11 $gCO_2e \cdot MJ^{-1}$ respectively. Maximum feedstock cost shows the least sensitivity of the three metrics, and it remains greater than the cost of offshore seaweed farming in all cases. Variation in seaweed composition gives the lowest and highest maximum feedstock cost values of $683 and $955 per tonne respectively. The increase in maximum feedstock cost is caused by a higher unfermentable fraction leading to greater animal feed production and higher co-product revenue.

6.6 Animal feed market limitation

The seaweed feed produced in the model has an average ash content of 56% and the seaweed animal feed production rate for the case study was 1.21 kg of dry mass per liter of ethanol produced. With seaweed ash containing 12% sodium or more by weight [15] and cattle tolerating feed with a maximum sodium content of 0.1% of total feed dry mass [61], the maximum amount of seaweed feed that can be included in cattle rations or *inclusion rate* for is 0.83% of total cattle feed dry mass. Assuming a 0.83% inclusion rate for beef, dairy, and swine and assuming a US feed market size equal to that considered by Bremer et al. [16], the US feed market could accept seaweed feed from 890 million liters of ethanol production per year. This would require 17 million tonnes of fresh *Saccharina latissima* per year, roughly equal to current global seaweed production [7], and it would require 4-5 ethanol plants with a typical production capacity of 200 $ML \cdot yr^{-1}$ [56]. For comparison, Bremer et al. calculated that US beef, dairy, and swine have maximum theoretical feed inclusion rates of 45%, 30%, and 27% respectively for corn ethanol animal feed and that the US feed industry can accept animal feed from 69 billion liters of corn ethanol production per year.

This chapter gave the results of the case study, presenting EROI, CI, near shore ethanol yield, maximum feedstock cost, and maximum drying and delivery cost for seaweed ethanol in BC, and showing the effect of animal feed production energy input, co-product credits, co-product revenue, and on these five performance metrics. It also included a sensitivity study showing the sensitivity of EROI, CI, and maximum feedstock cost to transportation, solar thermal seaweed drying, seaweed composition, seaweed farming, and seaweed to ethanol conversion.

The next chapter discusses the above results, the implications they have for seaweed ethanol production in BC, and their implications for seaweed ethanol production in general.

7 Discussion

This chapter discusses several exciting possibilities that emerge from the case study results documented in the previous chapter. The discussion is divided into six sections. The first covers points of interest specific to the BC case, the next four sections discuss points of interest for seaweed ethanol production in general, and the final section address the effect of key assumptions made in the case study model. Seaweed ethanol production in BC is discussed in Section 7.1 followed by discussions of animal feed production in Section 7.2, transportation system layout in Section 7.3, near shore farming potential in Section 7.4, seaweed composition in Section 7.5, and key assumptions in Section 7.6.

7.1 Seaweed ethanol production in BC

Seaweed ethanol production in the BC case is promising, but only if farming cost can be reduced and if adequate renewable drying systems can be designed. Despite the challenges of high water content, high ash content, and limited harvest season, the produced ethanol had very low CI and good EROI. Total near shore ethanol yield is equal to 28% of total BC gasoline use by volume, and BC's current ethanol demand could be supplied using 1-2 typically sized ethanol plants and farming 18% of the BC coastline at the same rate as China. Considering the minimal effect of the wet seaweed transport scenario shown in the sensitivity study, it may be feasible to transport farmed seaweed from any location on the coast to a central ethanol plant. Such a plant could be located in Bella Coola near geothermal resources [62] or in Kitimat near potential waste heat resources from an aluminum smelter. Both heat sources could replace fossil fuel for process heat and improve EROI and CI [63][64]. BC farming cost will need to be reduced as maximum drying and delivery cost was negative for all cases, but current farming systems are for small scale, artisanal seaweed production, and there is significant room for cost reduction [25]. Solar thermal seaweed drying may be an issue due to the high rainfall and humidity often experienced on the BC coast; however, seaweed is harvested during the summer months where rainfall is generally lower and solar resources are generally higher. Geothermal heat may be an option for continuously available drying heat as the BC coast has considerable geothermal resources [62].

7.2 Benefits from animal feed co-product

Animal feed may be a promising way to start the seaweed ethanol industry and to reduce energy input and GHG emissions through co-product credits, but feed distribution and feed market size may be a challenge. In the case of average co-product revenue and high near shore seaweed production cost, if both capital cost and operating cost are tripled, and seaweed production cost is doubled, the maximum drying and delivery cost is still $321 per tonne, thus animal feed revenue may be able to absorb the high cost of developing a first-of-a-kind seaweed ethanol plant. Because seaweed ethanol production may be possible without any animal feed sales for the ethanol plant cost considered in the case study, it may be possible to construct a large number of n-th of a kind seaweed ethanol selling low value co-products like methane or fertilizer if the seaweed feed market becomes saturated.

In addition to cost reduction, animal feed provided significant co-product credits in the case study. Co-product credits had the most significant influence of all the factors varied in the sensitivity study, and they may make it possible for seaweed ethanol to have negative carbon intensity and an EROI higher than most other biofuels. Additional research must be done to determine the true value of seaweed animal feed, feed inclusion rate in animal rations, and seaweed animal feed market size.

As the US feed market may only support 4-5 ethanol plants with the levels of sodium found in seaweed feed, a single seaweed ethanol plant may need to market and distribute feed to a large geographical area to find a market large enough to take its total feed output. Removing sodium from the feed could reduce the minimum distribution area required, and it would allow the feed market to sustain a larger number of ethanol plants. Methods to remove sodium from seaweed animal feed and the true value of co-product credits should also be investigated.

7.3 Flexibility in system layout

The flexibility in transportation distance shown in the sensitivity study opens up several opportunities for optimum system design regarding process heat sources and co-product production. Ethanol production facilities could be located near sources of geothermal heat [64] or industrial waste heat which could be used to reduce ethanol production fuel use and animal feed drying fuel use [63], and seaweed drying facilities could be located near good solar/geothermal resources or near low CI electricity sources to improve drying system COP and input CI.

Production facilities could be located in near sources of natural gas and low carbon electricity to avoid the use of coal which results in a significant increase in ethanol CI. Ethanol plants could also be located near livestock farming operations to increase the use of wet or modified animal feed which can significantly improve CI and EROI. These process improvement strategies should be considered for the design of seaweed ethanol production systems in the future.

7.4 Near shore farming potential

It is likely that ethanol production from near shore seaweed farming will be a valuable industry but a minor contributor to global biofuel production, and ocean fertilization may be required for substantial seaweed production. Near shore ethanol yield could be on the order of billions of liters per year, but it is two orders of magnitude lower than global gasoline consumption, therefore, open ocean seaweed farming may be required for seaweed ethanol to replace more than a few percent of global gasoline use. Fertilization may be required for some near shore farming regions to reach their full seaweed production potential, as is the case in Northern China [19], and fertilization may be needed for open ocean farming. Seaweed fertilizer emissions factors must be determined to determine the effect of fertilization on ethanol CI. As the case study production estimate is only a rough approximation of production potential, region specific studies of near shore seaweed production potential should be conducted.

7.5 The effect of seaweed composition

Seaweed composition has a significant influence on ethanol production, but additional work may be required to accurately predict its effect. Composition variation determines the length of the harvest season and thus determines if seaweed storage is required, and in the case study, composition variation resulted in EROI less than one. Accurate prediction of seaweed ethanol performance may require accurate prediction of seaweed composition as it varies throughout the year and as it varies between farm sites. A seaweed growth model similar to that given by Broch et al. [21] combined with a detailed model of local current, nutrient levels, weather, and farm structure geometry supply such a prediction, and this combination could be used as a screening tool for locating optimum seaweed farm sites.

7.6 The effect of key assumptions

The results of the case study depend on key assumptions in co-product credits, the cost and feasibility of renewable seaweed drying, and the future case of ethanol concentration and conversion yield. Because of the significant variation in CI and EROI caused by co-product credits, a study of credits similar to Bremer et al. [16] may be required to determine an accurate value of CI and EROI for seaweed ethanol. Ethanol performance is significantly affected by the performance of the solar thermal drying system. For solar thermal drying as considered in the case study, seaweed ethanol EROI matched that of corn ethanol for a COP of 14. Using a diesel generator to power a system with a COP of 14 raises CI from 10.1 $gCO_2e{\cdot}MJ^{-1}$ to 49.2 $gCO_2e{\cdot}MJ^{-1}$. A drying system with a COP of 14 or higher and with input energy CI of 140 $gCO_2e{\cdot}MJ^{-1}$ or lower is required to produce seaweed ethanol with a CI below 30 $gCO_2e{\cdot}MJ^{-1}$. The conservative case for ethanol concentration and conversion yield considered in the sensitivity study did not significantly affect ethanol performance. CI and maximum feedstock cost were not significantly affected, and EROI was reduced to 1.5 for the worst case. It may be possible to make low cost seaweed ethanol with a low CI without significant improvement in ethanol concentration or conversion yield if EROI can be improved. This could be done by using some amount of renewable heat for ethanol production or co-product production.

As discussed in this chapter, the case study results bring up several interesting points of discussion. Seaweed could meet the current need for ethanol in BC, but farming cost must be reduced and renewable drying systems must be proven feasible. Animal feed is a promising co-product, potentially compensating for high production costs and significantly improving EROI and CI through co-product credits. System layout is flexible due to low transportation energy use. Near shore farming production potential is small relative to current ethanol production and gasoline use. Seaweed composition variation has a significant influence of ethanol production, and solar thermal drying system COP and input CI have a significant effect on EROI and CI

The following chapter gives a summary of the general seaweed ethanol model, the case study, and thesis objectives, it gives a review of the most important results and discussion points, and it presents the conclusions of the thesis and recommendations for future work.

8 Conclusion

In this thesis, a general well-to-wheel model of seaweed ethanol was developed and applied to the case of ethanol production from *Saccharina latissima* farmed in BC, Canada. The objective was to contribute to a full lifecycle analysis of seaweed ethanol with a well-to-wheel model and to examine the well-to-wheel performance of seaweed ethanol through the BC case. To meet these objectives, the general model included a seaweed ethanol yield estimation tool to account for seaweed composition, and the case study included a model of large scale seaweed ethanol production based on the dry grind ethanol process. The case study also included revenue, energy input credits, and GHG emission credits from animal feed as a co-product, and it included a sensitivity study on input data.

Despite the challenges of high water content, high ash content, and limited harvest season, seaweed ethanol is a promising biofuel with low CI, good EROI, and promising finances for the BC case study. Ethanol in the scenario considered had a CI of 10.1 $gCO_2e \cdot MJ^{-1}$ and EROI of 1.78. Considering a natural gas powered production facility, a range of co-product credits, and various levels of animal feed drying, CI ranged from -42 to 33 $gCO_2e \cdot MJ^{-1}$, and EROI ranged from over 200 to 1.33. Considering a coal powered ethanol production facility with these same ranges, CI varied from 37.8 to 65.3 $gCO_2e \cdot MJ^{-1}$. The ethanol yield from near shore seaweed farming was estimated at 1.3 billion liters per year for BC and at 18.4 billion liters per year for total global coastline. This would require 7 and 90 typically sized ethanol plants respectively, and in the BC case, it is equal to 28% of provincial gasoline demand by volume. Maximum feedstock cost was $188 per tonne of dry seaweed without co-product revenue, and it ranged from $743 per tonne to $987 per tonne with co-product revenue Maximum drying and delivery cost was negative for current BC seaweed farming costs and for the case of high offshore farming cost with no co-product revenue. It ranged from $46-166 per tonne of dry seaweed in the other cases without co-product revenue, and it ranged from $223-965 per tonne with co-product revenue. Seaweed animal feed has sodium content on the order of 12% of total dry mass which limits its inclusion rate in animal feed to the order of 0.8% of total feed dry mass. At this inclusion rate, the entire US cattle and swine feed markets could only accommodate the annual feed production from 4-5 typically sized ethanol plants.

The case study and sensitivity study revealed several interesting points of discussion relating to production in BC, animal feed production, seaweed transportation, seaweed farming, seaweed composition, and seaweed drying.

- Seaweed ethanol production is promising in BC, but seaweed farming costs must be reduced and solar thermal or geothermal seaweed drying must be proven feasible.
- Animal feed production significantly improves the finances of seaweed ethanol and may help start the seaweed ethanol industry by absorbing the cost of a first-of-a-kind seaweed ethanol plant. Maximum drying and delivery cost would still be significantly positive if seaweed ethanol conversion facilities were triple the cost of dry grind conversion and near shore farming cost double the value given in literature.
- Energy and emissions in transportation are relatively small, allowing long transportation distances and flexibility in locating ethanol plants, drying sites, and farms.
- Near shore seaweed farming appears to have significant ethanol production potential, but offshore seaweed farming may be required for seaweed ethanol to significantly impact global fossil fuel consumption.
- Seaweed composition varies significantly depending on time of year, environmental conditions, and seaweed's natural growing cycles, and it has a significant influence on EROI
- Seaweed drying is necessary to support ethanol production in regions like BC and northern China that have a limited seaweed harvest season, and drying system COP and input CI have a significant effect on EROI and CI.

Seaweed ethanol shows promise as an outstanding, low emission biofuel that may be affordable to produce even in regions that require seaweed drying and storage, and that animal feed revenue may compensate for the additional cost of developing a first-of-a-kind seaweed ethanol plant; however, this analysis is preliminary in nature and significant additional analysis is required to validate these conclusions.

8.1 Recommendations

To enhance the model and to confirm the conclusions of the case study, the following improvements are recommended.

- Determine the true revenue from seaweed animal feed and seaweed animal mineral supplements, and determine maximum inclusion rates and seaweed feed market size.
- Investigate the removal of sodium from seaweed ethanol co-products to increase inclusion rates, feed value, and feed market size.
- Conduct a co-product credit study similar to Bremer et al. [16] for seaweed animal feed, seaweed mineral compliments, and seaweed fertilizer to determine accurate credit values and thus accurate CI and EROI values for seaweed ethanol.
- Create a more accurate model of the seaweed conversion facility for cost and energy use that more accurately accounts for process differences and considers the effect of seaweed salt content on conventional ethanol processing equipment, and create a more accurate model of bulk seaweed storage that considers the effect of salt content, seaweeds propensity to rehydrate in the presence of humid air, and differences in material handling between corn grains and bulk seaweed.
- Examine the COP, input CI, and cost for solar thermal and geothermal seaweed drying in regions that require seaweed storage, considering local weather, solar or geothermal resources, cost of labor, and existing infrastructure.
- Develop a farm site specific seaweed production model to calculate seaweed composition and analyze farm performance based on a growth model like that of Broch et al. [21], and conduct region specific studies of seaweed farming potential and ethanol production potential.
- Determine GHG emission factors for ocean application of fertilizer as they currently unknown and fertilizer application may be required in many seaweed production regions.
- Examine solar and geothermal drying for animal feed production and examine geothermal heat for the ethanol conversion plant to improve EROI and CI in the BC case

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Appendix A - Ideal ethanol yield

The ideal yield is calculated from net result of the metabolic process used to convert each fermentable component into ethanol assuming that 100% of fermentable component is converted. The conversion process and the molar ideal ethanol yield for mannitol, laminarin, and alginate are described below.

Mannitol

Mannitol is a simple sugar alcohol ($C_6H_{14}O_6$). In ethanol production, mannitol is first converted to fructose-6-phosphate then converted to pyruvate via glycolysis or the Entner-Doudorof pathway [9]. Pyruvate is then converted to ethanol via fermentation. Unlike the fermentation of glucose, mannitol fermentation does not result in a redox balance. Oxygen and an active electron transport chain, H_2 production, or transhydrogenase enzymes are required to effect a balance which limits the number of microorganisms that can metabolize mannitol (Horn). Each molecule of mannitol yields 2 molecules of ethanol and 2 molecules of CO_2.

Laminarin

Laminarin is a polymer of glucose ($C_6H_{12}O_6$) and a small quantity of mannitol. It is largely polymers of glucose that terminate in a single mannitol molecule, but it also includes some polymers of pure glucose. Both have varying degrees of branching and varying chain lengths. In ethanol production, laminarin is enzymatically decomposed into free glucose and mannitol molecules. The glucose is converted first into pyruvate via glycolysis and then into ethanol through fermentation [65], and the mannitol is converted as described above. Each glucose and each mannitol molecule yield 2 ethanol molecules and 2 CO_2 molecules.

Read et al. [66] found the composition of laminarin from the brown seaweed Laminaria digitata to be 73% chains of 20-30 glucose units that terminated in a mannitol molecule and 27% chains of 20-28 glucose units without mannitol. Based on the composition computed by Read et al., the laminarin sample was 3% mannitol and 97% glucose by weight giving an ideal ethanol yield of 0.5679 $gEtOH \cdot gLaminarin^{-1}$. Because data on the exact composition of laminarin from other species of brown seaweed was unavailable, ideal yield is approximated assuming that laminarin contains only glucose. Applying this assumption to conversion of the sample examined by Read et al. gives a yield of 0.5683 gEtOH·gLaminarin^{-1}, only 0.05% higher than the true ideal yield.

Alginate

Alginate is a polysaccharide of mannuronate and guluronate with varying mannuronate:guluronate ratio, varying degrees of branching, and molar mass ranging from 10,000 to 600,000 g·mol^{-1} [67]. Because mannuronate and guluronate have identical molecular formulae and identical ethanol yield per mole, the ideal yield from alginate can be calculated considering alginate to be a polymer of the form $(C_6H_8O_6)_n$. Following the metabolic pathway described by Wargacki et al. [12], each $C_6H_8O_6$ monomer yields 2 ethanol molecules and 2 CO_2 molecules.

Results

Ideal ethanol yield per unit mass, ψ_i, for mannitol, laminarin, and alginate is calculated using Eq. (0.1) with input data and results shown in Table A-1.

$$\psi_i = \frac{2M_{EtOH}}{M_i} \tag{0.1}$$

Where M_{EtOH} is the molar mass of ethanol, and M_i is the subunit molar mass of feedstock i.

Table A-1: Ideal ethanol yield for brown seaweed and corn starch

Polysaccharide/ monosaccharide	Sub unit structure	Subunit ethanol yield [mol·mol^{-1}]	Subunit molar mass [g·mol^{-1}]	Ideal ethanol yield, [gEtOH·g^{-1}]
Alginate	$[C_6H_8O_6]_n$	2[a]	176.12	0.523
Laminarin[c]	$[C_6H_{10}O_6]_n$	2[b]	162.14	0.568
Mannitol	$C_6H_{14}O_6$	2[b]	182.17	0.506
Amylose/Amylopectin (corn starch)	$[C_6H_{10}O_6]_n$	2	162.14	0.568
Glucose	$C_6H_{12}O_6$	2	180.16	0.511

[a] From metabolic path given in Wargacki et al. [12]. [b] From metabolic path given by Horn [9]. [c] Laminarin is largely composed of glucose but contains a small amount of mannitol. Ideal yield is calculated assuming that laminarin contains only glucose which results in negligible error. Ethanol yield assuming pure glucose is only 0.05% higher the true ethanol yield calculated using the composition of laminarin samples analyzed by Read et al. [66]

Appendix B - Input data

Model parameters are broken into nine groups: seaweed production, drying, ethanol yield, animal feed production and credits, transportation and distribution, CI, global ethanol production, and cost analysis. Each contains the values used in the main analysis and expected ranges considered in the sensitivity study as shown in Table B-1 to Table B-9. Expected ranges were not determined for non-sensitive inputs.

Table B-1: Seaweed production

Name	Symbol	Value	Range	Units	Source
Sporeling tank electrical power draw	P_T	300	50-300[a]	W	[24]
Sporeling batch culture time	t_C	8	-	weeks·batch^{-1}	[24]
Horizontal rope seaweed production rate	R_P	18.5	-	kg·m^{-1}yr^{-1}	[24]
Horizontal rope seeded per sporeling batch	L_T	600	-	m·batch^{-1}	[24]
Skiff fuel use at cruising speed	F_{SC}	0.271	-	L·km^{-1}	[68]
Skiff fuel use at idle (700 RPM)	F_{SI}	0.757	-	L·hr^{-1}	[68]
Sporeling rope installation time	t_{INST}	0.75	-	min·m^{-1}	[24]
Installation work day	t_{WD}	8	-	hr	[24]
Spore bearing frond collection time	t_{FC}	10	-	min·batch^{-1}	[24]
Sporeling batches produced per frond collection trip	n_B	10	-	batch·trip^{-1}	[24]
Horizontal rope harvesting time	t_{HARV}	0.1	-	min·m^{-1} [b]	[24]

[a] The current system power draw is considered in the model and a future case of reduced power consumption is considered in the sensitivity study. [b] 2 minutes to collect one 20m horizontal rope of kelp

Table B-2: Drying

Name	Symbol	Value	Range	Units	Source
Dry seaweed moisture content (wet basis)	M_d	0.22	-	-	[19]
Seaweed water removal heat requirement	H	4.0	-	$MJ\cdot kg^{-1}$	[25][69]
Solar thermal system COP	COP_H	30	5.4-30	-	[a]

[a] COP lower bound is for the a heat pump based system with thermal storage described by Xie et al. [46], and the upper bound is an approximation for simple seaweed drying systems using only an air circulation fan.

Table B-3: Ethanol yield

Name	Symbol	Value	Range	Units	Source
Conversion efficiency	$\eta_{Alginate}$ $\eta_{Laminarin}$ $\eta_{Mannitol}$	0.9	0.7-0.94	-	[12][35]
Ideal ethanol yield	$\psi_{Alginate}$	0.523	-	-	[a]
	$\psi_{Laminarin}$	0.568	-	-	[a]
	$\psi_{Mannitol}$	0.506	-	-	[a]
Dry weight mass fraction[b]	$f_{Alginate}$	0.131	[c]	-	[6]
	$f_{Laminarin}$	0.18.5	[c]	-	[6]
	$f_{Mannitol}$	0.201	[c]	-	[6]
Fresh seaweed moisture content (wet basis)[b]	M_f	0.808	[c]	-	[6]

[a] Appendix B. [b] Values are shown for September 1947 composition as an example. The case study model is run for the composition in September 1947 and again for composition in October 1947, and the results are averaged. [c] September 1947 is used for all calculations in the sensitivity study aside from the seaweed composition cases discussed in Section 5.6.

Table B-4: Ethanol conversion input

Name	Symbol	Value	Range	Units	Source
Ethanol production fuel scaling factor	δ_{EF}	1	1-2[a]	-	[47]
Natural gas consumption in dry grind ethanol production	$E_{EF,C}$	4.91	-	$MJ\cdot L^{-1}$	[16]
Total electricity consumption in dry grind ethanol production	$E_{EE,C}$	0.634	-	$MJ\cdot L^{-1}$	[16]
Fraction of total dry grind electricity consumption used for feed processing	A	0.40	-	-	[70]
Dry grind animal feed drying fuel[b]	$E_{CF,D}$	4.44	-	$MJ\cdot kg^{-1}$	[16]
Dry grind animal feed production rate	D_{corn}	0.632	-	$kg\cdot L^{-1}$	[16]
Ethanol plant production capacity	P_{cap}	100	-	10^6 L	[71]

[a] As the maximum ethanol concentration achieved through fermentation decreases from the typically achieved 12% by volume [35] to 4.7% by volume [12], energy consumption in distillation doubles [47]. [b] Energy required for drying the average mix of wet, modified, and dry distiller's grains with solubles produced by the dry grind ethanol plants reviewed by Bremer [16].

Table B-5: Animal feed production and credits

Name	Symbol	Value	Range	Units	Source
Wet feed mass fraction	$f_{C,WF}$	0.01[a]	0-1	-	[16]
Modified feed mass fraction	$f_{C,MF}$	0.32[a]	-	-	[16]
Dry feed mass fraction	$f_{C,DF}$	0.67[a]	0-1	-	[16]
Wet feed drying fuel[b]	$E_{CF,WF}$	0	-	$MJ \cdot kg^{-1}$	[16]
Modified feed drying fuel[b]	$E_{CF,MF}$	2.59	-	$MJ \cdot kg^{-1}$	[16]
Dry feed drying fuel[b]	$E_{CF,DF}$	5.41	-	$MJ \cdot kg^{-1}$	[16]
Feed displacement energy credit[c]	$K_{N,F}$	3.27	0-5.06	$MJ \cdot L^{-1}$	[16]
Feed displacement emissions credit[c]	$K_{M,F}$	19.9	0-28.3	$gCO_2e \cdot L^{-1}$	[16]
Mineral supplement displacement energy credit[c]	$K_{N,R}$	0	0-5.06	$MJ \cdot L^{-1}$	[16]
Mineral supplement displacement emissions credit[c]	$K_{M,R}$	0	0-28.3	$gCO_2e \cdot L^{-1}$	[16]

[a] The average mix wet, modified, and dry distiller's grains with solubles produced by dry grind ethanol plants surveyed by Bremer et al. [16]. The case of $f_{G,WF} = 1, f_{G,DF} = 0$ and the case of $f_{G,WF} = 0$, $f_{G,DF} = 1$ give the extremes of the feed production type study. [b] Fuel input calculated for a typical grains production rate of 0.632 $kg \cdot L^{-1}$. [c] All four co-product credit values are varied together in the sensitivity study. All credits equal to zero and all credits equal to the maximum indicated value give the extremes of the co-product credit study.

Table B-6: Transportation and distribution

Name	Symbol	Value	Range	Units	Source
Ethanol vapor loss in distribution	m_{EL}	0.05	-	$kg \cdot kg^{-1}$	[52]
Ethanol 100 year GWP	GWP_{EtOH}	1.3	-	$gCO_2e \cdot g^{-1}$	[72]
Skiff fuel use factor, full load	F_{SK}	15.0	-	$MJ \cdot tonne^{-1}km^{-1}$	[73]
Barge fuel use factor	F_{BR}	0.566	-	$MJ \cdot tonne^{-1}km^{-1}$	[53]
Train fuel use factor	F_{TN}	0.219	-	$MJ \cdot tonne^{-1}km^{-1}$	[53]
Fuel truck fuel use factor	F_{TK}	2.09	-	$MJ \cdot tonne^{-1}km^{-1}$	[53]
Transportation and distribution distances					
sporeling culture facility to farm structure	d_X	10	-	km	-
Farm structure to drying facility	d_1	1.5	1.5-0.6[a][b]	km	-
Drying facility to conversion facility	d_2	200	68-200[b]	km	-
Conversion facility to train loading site	d_3	720	0-720[b]	km	-
Train loading site to blending facility	d_4	620	0-620[b]	km	-
Blending facility to fuel station	d_5	25	12.5-25[b]	km	-

[a] For the wet transport scenario shown in Figure 5-2B, fresh seaweed is transported 0.6km by skiff before being loaded onto the barge. [b] Simultaneously varied distances for the minimum transport scenario shown on the left, distances for the wet transport scenario shown on the right

Table B-7: Carbon intensity for energy consumed

Name	Symbol	Value	Range	Units	Source
Natural gas	I_{NG}	50	-	$gCO_2e \cdot MJ^{-1}$	[74]
Coal	I_C	97.3	-	$gCO_2e \cdot MJ^{-1}$	[75]
Electricity[a]	I_{ELEC}	5.6	5.6-244	$gCO_2e \cdot MJ^{-1}$	[76]
Gasoline	I_G	90.2	-	$gCO_2e \cdot MJ^{-1}$	[55]
Barge fuel	I_{BR}	104	-	$gCO_2e \cdot MJ^{-1}$	[53]
Train fuel	I_{TN}	106	-	$gCO_2e \cdot MJ^{-1}$	[53]
Fuel truck fuel	I_{TK}	92.9	-	$gCO_2e \cdot MJ^{-1}$	[53]
Solar thermal system input[b]	I_{ST}	5.6	5.6-275	$gCO_2e \cdot MJ^{-1}$	[76]

[a] BC grid electricity and coal heavy Alberta grid electricity are considered as extremes. [b] The solar thermal system is assumed to be powered by renewable electricity similar in CI to BC grid electricity or by a diesel generator (34% efficient, 93.3 $gCO_2e \cdot MJ^{-1}$ input fuel).

Table B-8: Global ethanol production

Name	Symbol	Value	Range	Units	Source
China annual seaweed production	P_{CH}	11.1	-	10^6 tonne·yr^{-1}	[77]
World coastline length	$L_{CL,W}$	356,000		km	[78]
BC coastline length	$L_{CL,BC}$	25,725	-	km	[79]
China coastline length	$L_{CL,CH}$	14,500	-	km	[78]
Gasoline to ethanol blend equivalence[a]	X_{E10}	1	-	$L \cdot L^{-1}$	[54]

[a] Gives the quantity of gasoline replaced by one liter of ethanol in an E10 blend for the same distance driven.

Table B-9: Cost analysis

Name	Symbol	Value	Range	Units	Source
Rate of return	i_{ROR}	0.20	-	-	-
Ethanol plant operating life	t_{OL}	10	-	yr	[71]
Wholesale ethanol price[a]	W_{EtOH}	0.83	-	$\$\cdot L^{-1}$	[80]
Wholesale seaweed feed price[b]	W_{GR}	1250	0-1900	$\$\cdot tonne^{-1}$	[81][82]
2012 CAD/USD exchange rate	R_{EX}	0.993	-	$CAD\cdot USD^{-1}$	[60]
Inflation correction factor	N_F	1.38	-	2012 USD· 1999 USD^{-1}	[59]
Seaweed bulk density	B	0.6	-	$kg\cdot m^{-3}$	[83]
Silo capital cost[c]	C_{Sl}	21	-	$\$\cdot m^{-3}$	[84]
Ethanol plant capital costs[d]					
Feedstock handling	S_{FH}	3.56	-	10^6 \$	[71]
Fermentation	S_{Fr}	6.30	-	10^6 \$	[71]
Distillation	S_{Ds}	7.26	-	10^6 \$	[71]
Animal feed production	S_{AF}	14.39	-	10^6 \$	[71]
Storage and load out	S_{SLO}	2.06	-	10^6 \$	[71]
Wastewater treatment	S_{WT}	1.37	-	10^6 \$	[71]
Air compressor	S_{AC}	0.14	-	10^6 \$	[71]
Ethanol plant operating costs[d]					
Raw materials	O_{RM}	2.19	-	$10^6\ \$\cdot yr^{-1}$	[71]
Denaturant	O_{Dn}	0.82	-	$10^6\ \$\cdot yr^{-1}$	[71]
Energy input	O_{EI}	5.48	-	$10^6\ \$\cdot yr^{-1}$	[71]
Labor, supplies, and overhead	O_{LSO}	4.25	-	$10^6\ \$\cdot yr^{-1}$	[71]

[a] Average for Vancouver for Jan-Sept 2012. [b] Chosen price is average of the maximum and minimum kelp animal feed prices found online, 600 $\$\cdot tonne^{-1}$ and 1900 $\$\cdot tonne^{-1}$ respectively. [c] Converted to 2012 CAD [59][60]. [d] For 95 $ML\cdot yr^{-1}$ capacity.