DANISH TECHNOLOGICAL INSTITUTE

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Macro Algae Logistics

Prepared by:
Danish Technological Institute / Biomass & Biorefinery
Teknologiparken
Kongsvang Allé 29
8000 Aarhus C

Authors:
Leivur Gilli Trond & Jørgen Hinge

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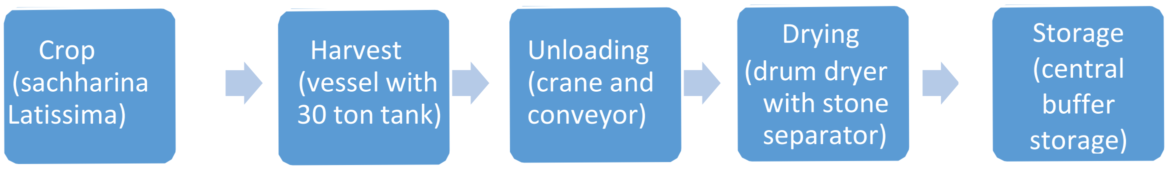
1. Summary

The biomass logistics tool developed within the project "EUROBIOREF" has been modified to be able to handle scenarios for aquatic biomass, e.g. macro algae.
A scenario with 5 supply chain elements has been elaborated with the brown algae *Saccharina latissima* as biomass crop:



The seeding and cultivation of the *S. Latissima* crop is described separately and the different processes in the cultivation will be included in the logistic tool in the next stage. For now, a price for the crop is estimated at the time of the harvest.
Data sheets for each of the supply chain elements has been elaborated and fed into the logistics model.

Main scenario features and assumptions:

- Country: Denmark
- Crop: *Saccharina latissima*
- Cultivation: on-land seeding of growth lines with off-shore cultivation
- Annual demand by "customer": 36.000 tons DM
- Annual yield: 30 tons fresh weight/hectare

2. Supply chain

Seeding

The term 'macroalgae' covers a wide variety of organisms. Some can be cultivated vegetative planting, while other species requiring dedicated seeding facilities as they go through a separate reproductive cycle, involving alternation of generations. Vegetative cultivation involves harvesting small cuttings of seaweed from the plants and placing these in an environment that will sustain their growth. When the cuttings regrown to a suitable size, they are harvested, and small cuttings taken to facilitate the subsequent generations of harvest. The suitable environment varies among species, but must meet requirements for salinity of the water, nutrients, water movement, water temperature and light.

Cultivation involving a reproductive cycle, with alternation of generations, is necessary for many seaweeds; for these, new plants cannot grow by taking cuttings from mature ones. This is typical for many of the brown seaweeds, and *Laminaria* species are a good example; their life cycle involves alternation between a large sporophyte and a microscopic gametophyte -two generations with quite different forms. The sporophyte is harvested as seaweed, and to grow a new sporophyte it is necessary to go through a sexual phase involving the gametophytes.

The mature sporophyte releases spores that germinate and grow into microscopic gametophytes. The gametophytes become fertile, release sperm and eggs that join to form embryonic sporophytes. These slowly develop into the large sporophytes, the crop to be harvested.

The principal difficulties in this kind of cultivation lie in the management of the transitions from spore to gametophyte to embryonic sporophyte; in land-based facilities with careful control of water temperature, nutrients and light. Where cultivation is used to produce seaweeds for the hydrocolloid industry (agar and carrageenan), the vegetative method is mostly used, while the principal seaweeds used as food must be taken through the alternation of generations for their cultivation.

Saccharina latissima (Sugar kelp) is seeded by the reproductive gametophytes/sporophyte cycle, but can be regrown by cuttings for a limited amount of cycles (6 harvests being the current optimal in the Faroe Islands) with diminishing returns. The steps for *Saccharina latissima* seeding are as follows:

1. Collection of wild embryonic sporophytes released from natural populations
2. Nursing the gametophytes in land-based seeding facilities (duration 4-6 weeks). The sporophytes are placed in tanks with the chosen cultivation substrate (lines, nets, mats), and will slowly attach themselves.
3. Once the sporophytes have attached, the next task is removal of the lines/nets/mats from the controlled environment, they are transferred to the cultivation site placed upon a cultivation installation in the open ocean.

Cultivation

Deployment of the seeded substrate (lines, nets, mats) is done directly into the sea - on cultivation installations. The size of a commercial seaweed farm can range from a few hectares to more than 1000 hectares, and to transition from small scale to large-scale cultivation requires the installations to be deployed in deep water on offshore sites. To ensure good growth conditions the cultivation sites need to supply the seaweeds with light and nutrients, upwelling areas with high primary production or areas with fertilization with nitrate and ammonium released from fish (integrated multi trophic aquaculture) are preferable.

Cultivation requires an installation specifically designed for the task. Several different types of installations currently exist, most employing technology assimilated from other marine sectors, such as mussels, long-line and fixed gillnets. Common for all these installations is that mooring and structural components are not removed for seeding, but stay in place, and the seeded material is deployed once ready. From seeding and until harvest the only activity is monitoring, to check that the growth of the seaweed is progressing according to plan. Once a desired maturity of the macroalgae is reached, harvesting commences.

The steps of *Saccharina latissima* cultivation (post-seeding) are as follows:

1. Deployment of seeded substrate
2. Monitoring of growth, taking samples.
3.

Samples may be taken during the cultivation phase to ensure that the desired compounds are present. Sales price is often based upon the compounds within the cultivated macroalgae, and these often show a pronounced seasonal variation, with proteins being readily available from the biomass in the spring and early summer, while sugars replace the proteins during the autumn and winter.

Harvest

Harvest of the *S. Latissima* crop is carried out with specialized vessels – figure 2.1.

Figure 2.1 Algae harvesting vessel

The following operations are covered by the term “harvest”:

- Main ropes with 6 m lines are brought onto the vessel as the vessels moves along the rope in it’s entire length. The 6 m lines are detached from the main rope, and algae biomass is stripped from the lines
- New sporulated 6 m lines are attached to the main rope to replace the “harvested lines”
- The algae biomass is stored in a central tank in the vessel; after simple on-deck running of of water, the biomass is stored the tank with an average dry matter content of 17%
- When the central tank is filled (30 tons of fresh weight = app 5,1 ton DM), the vessel sails to “harbor” for unloading

<u>Specifications of the harvesting vessel</u>

Price of equipment - Basic machine - Dedicated equipment 1 Total	 Euro Euro Euro	 750.000 600.000 1.350.000
Energy consumption	GJ/ton DM output	4,15
CO_2-emission	Kg CO_2/ton DM output	364
Input/output ratio	% DM output/input	95
Efficiency	%	90
Fuel consumption	Ltr diesel/hour	57
Utilization - Basic equipment - Dedicated equipment	 Hours/year Hours/year	 2160 720
Staff	Number of persons	2,25 (highly skilled staff) (1captain=1,25 staff)

It is assumed, that the vessel can be used for other purposes, when it's not occupied by algae harvesting. This is reflected in the assumption that the "basic machine" has 2160 operation hours annually, whereas some "dedicated equipment" at the vessel is used only during algae harvest.

Unloading

Unloading covers the following operations

- Unloading by crane of algae biomass from the harvesting vessel, onto
- Conveyor belt

The algae material is dropped from the conveyor belt at the site of the drum dryer.

Specifications of the unloading equipment (crane and conveyor)

Price of equipment	Euro	300.000
Energy consumption	GJ/ton DM output	0,05
CO_2-emission	Kg CO_2/ton DM output	2,5
Input/output ratio	% DM output/input	90
Efficiency	%	75
Fuel consumption	kWh/hour	50
Utilization	Hours/year	720
Staff	Number of persons	1

(A front end loader probably needs to be included as an extra supply chain element in order to feed the material into the drum dryer…)

Preprocessing

Preprocessing covers the following operations:

- Drying of the algae material in drum dryer
- Device for separation of stones and other inorganic elements.

Specifications of the preprocessing equipment

Price of equipment	Euro	200.000
Energy consumption	GJ/ton DM output	10,4
CO_2-emission	Kg CO_2/ton DM output	915
Input/output ratio	% DM output/input	95
Efficiency	%	80
Fuel consumption	kWh/ton DM output	3483
Utilization	Hours/year	1400
Input/output DM content	%/%	17/70

The algae biomass entering the drum dryer is assumed to have a dry matter content of 17%, and it must be dried up to 70% DM in order to have a somewhat inactive biomass which can be stored without a greater loss due to biological activity.

Buffer storage

From the drum dryer/stone separator, the biomass is dropped directly into the storage. It is assumed that the biomass is rather stable at this point and can be stored without big losses due to degradation. In the basic scenario, an open storage of the biomass is therefore applied. A minor degradation is anticipated.

Specifications of the buffer storage

Price of equipment	Euro	0
Energy consumption	GJ/ton DM output	0
CO_2-emission	Kg CO_2/ton DM output	0
Average storage period	Months	3
Input/output ratio	% DM output/input	91,1
Efficiency	%	-
Fuel consumption	kWh/hour	0
Utilization	Hours/year	-

3. Results and cost analysis

The total costs for the chosen scenario are calculated at 1179 Euro/ton DM (handling costs only) or 1724 Euro/ton DM (including costs for seeding and cultivation of the crop), respectively – as shown in table 3.1.

Availability	Ton DM	**Unlimited**
Biomass bulk density	kg dry matter [or end product]/m^3	**250**
Dry matter content	Average scenario % dry matter	**70**
DM output/input	Output/input - %	**73**
Efficiency (minimum value)	%	**75**
Cost of handling	Euro/ton DM [of end product]	**1179**
Cost of biomass	Euro/ton DM [of end product]	**1724**
Energy consumption	GJ/ton DM [of end product]	**17,9**
CO_2 emission	kg/ton DM [of end product]	**1565**
Security of supply	80 % probability that actual supply is not delayed more than a total of [-] of weeks	**0**
Minimum volume	tons DM/season	**603**

Table 3.1. Key figures for the chosen scenario.

The energy consumption is calculated at 17,9 GJ/ton DM delivered "at the gate" (of the biorefinery/factory process).

The algae biomass is delivered with a DM content of 70% (as compared to 17% in the harvested biomass after rough de-watering at the harvesting vessel)
In figure 3.1 the costs of each supply chain element are shown. It can be seen, that besides the price of the algae (ready for harvest), and the two important supply chain elements are harvest and drying. For the harvesting vessel, the rather limited tank capacity of the vessel (30 tons fresh weight) is an important factor. Depending on the distance from the harvesting site to the harbor, it

could be feasible to reload the harvested material onto a barge with large capacity (>1000 tons fresh weight) for more effective

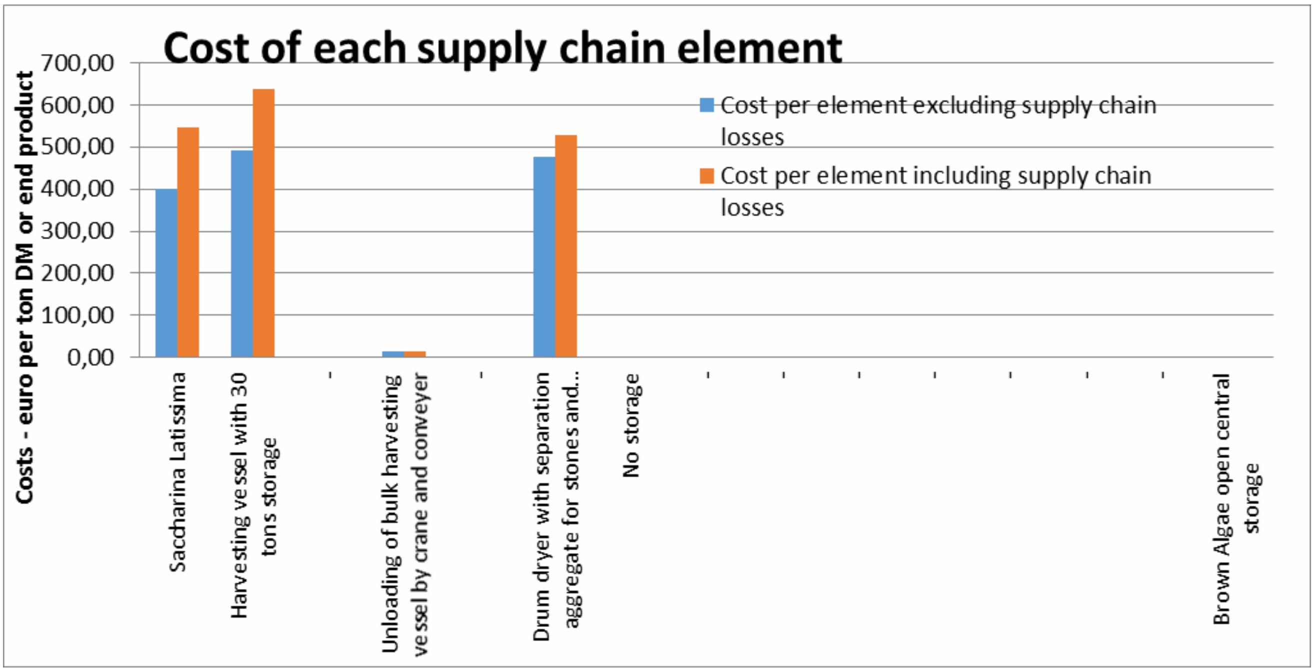


Figure 3.1. Cost of the supply chain elements in the chosen scenario (basic).

For the drying of the biomass, the energy consumption is the crucial factor. A reduction of the energy consumption of 70% (as suggested by some DTI experts) will result in drying costs being reduced to 162 Euro/ton DM (figure 3.2), as compared to 476 Euro/ton DM in the basic scenario (figure 3.1).

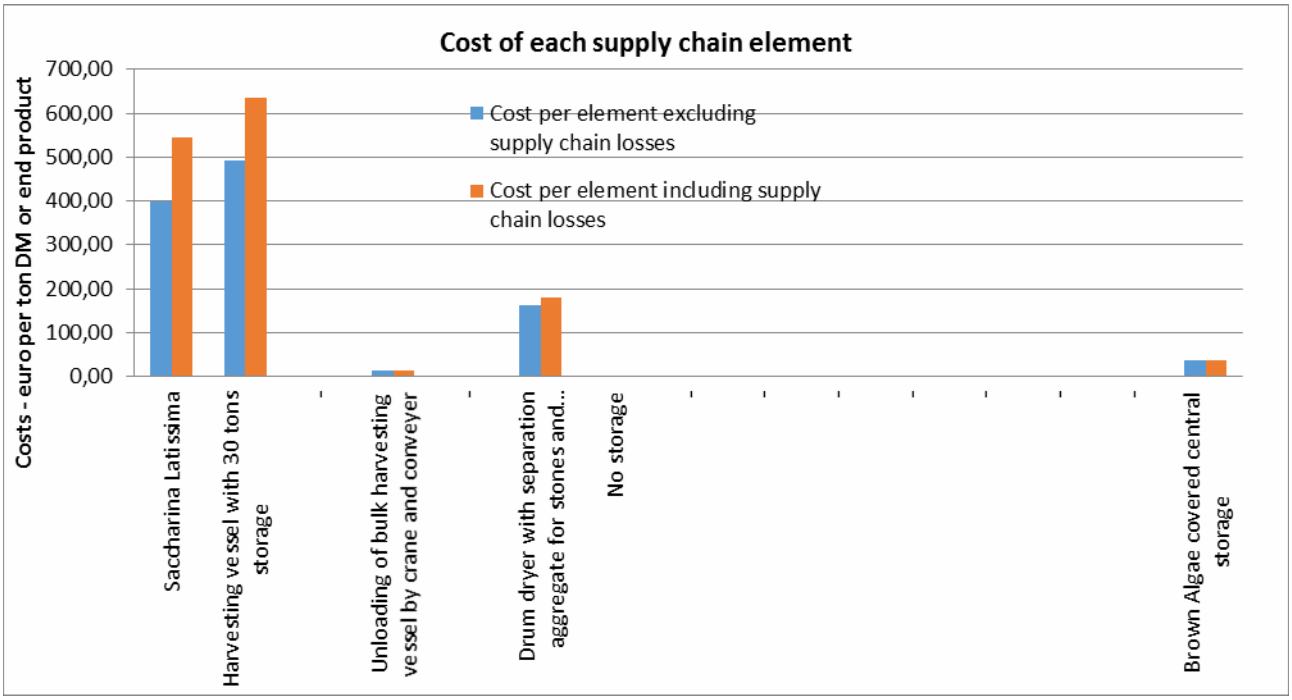


Figure 3.2. Cost of the supply chain elements – reduction of energy consumption for drying by 70%
and increased investment (1 mill Euro) in central storage.

From figure 3.2 it can also be seen, that increased investment in central storage facilities by 1 mill Euro (in the basic scenario, set to 0 Euro…), results in only a minor increase in total costs for the supply chain.

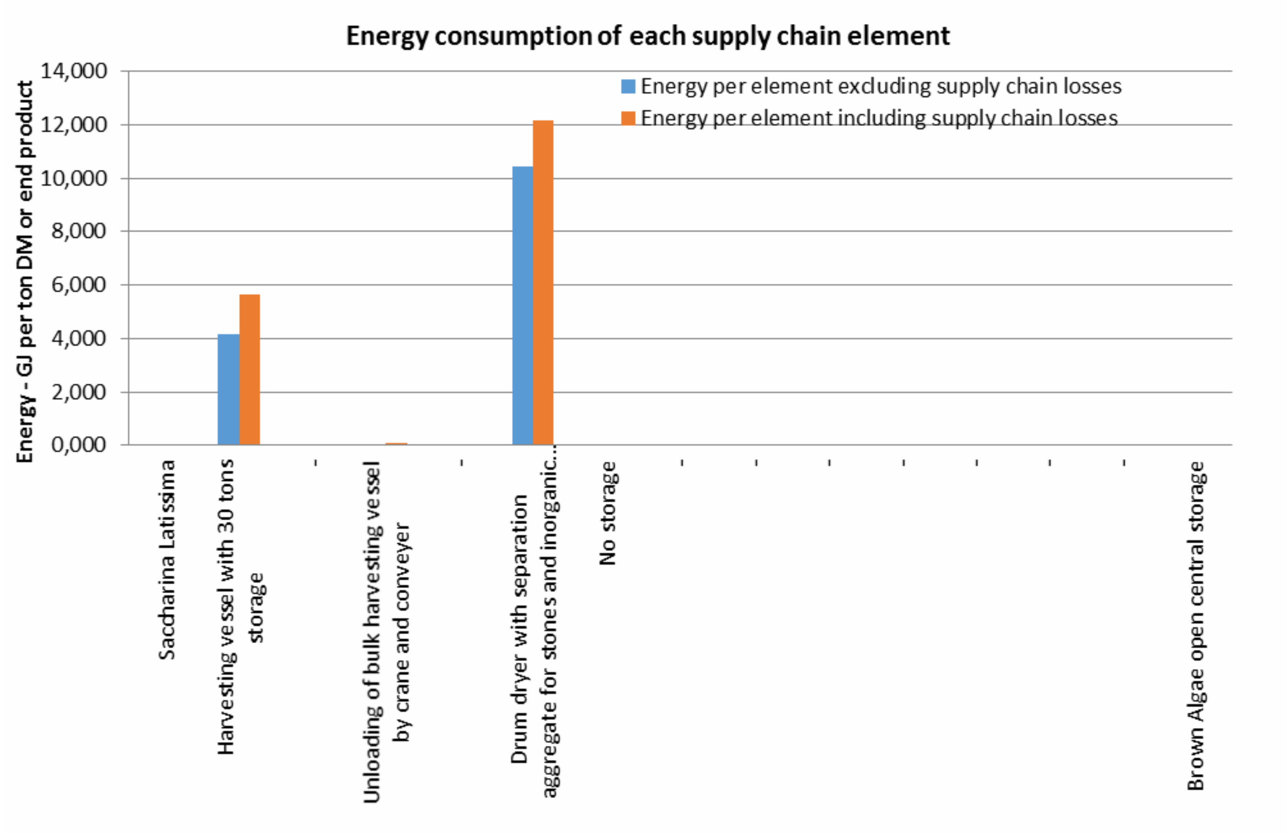


Figure 3.3.Energy consumption of the supply chain elements in the basic scenario.

As can be seen from figure 3.3, more than 2/3 of the energy consumption of the basic supply chain is a result of the drying of the biomass, the operation of the harvesting vessel being the other significant contribution.

4. Conclusions

The handling of algae biomass is well suited for the biomass logistics tool developed within the EUROBIOREF project. Some modifications has to be completed in order to include sporulation and growth of the algae biomass.

The validity and outcome of the logistic model is highly depending on the quality of the input into the data sheets for each handling operation. During this work, it has become evident, that there is still a lack of valid data for full scale cultivation of large quantities of macro algae, as well as for crucial supply chain elements, such as harvesting equipment.
However, the structure of the data sheets and the combination of these into the supply chain is established and “up and running”, so as research and full scale trials reveal more valid data, this can be included in to the work as it comes along.

ANNEX 1. DATA SHEET

The EUROBIOREF project is supported within the 7[th] Framework Program for Research and Technological Development

This document is a data-sheet prepared to feed into the logistic model

Category:	Crop					
Crop:				x		
Nomenclature | Sheet ID:	Saccharina Latissima crop		171	x		
Country:	Denmark	DK	2			Insert customised figures in green cells
Date:						
Contact:	Jørgen Hinge, Technological Institute, jhi@teknologisk.dk					
Details					Source	**Remarks**
Crop ID related to harvest method	Saccharina Latissima					
Timing of harvest	The harvesting takes place in May - with additional harvesting is possible twice until November. However, a lot of fouling will occur in the summer months					
Storage	In order to be able to store the algae biomass without excess biological activity (causing degradation/decomposition) the harvested material mus be dried from app 17% DM to app 70% DM					
References					1	
	Hinge J. et al. (2013). Assessment.					
Specifications and data	**Units**	**Range**	**Figure used**		***Ref***	
Biomass						
Description						
Dry matter	% dry matter		17	x	*0*	
Yield	ton biomass per hectare		30,0	x	*0*	
Oil content	% of DM	N/A		x		
Bulk density of seeds	kg biomass/m³	N/A				
Bulk density of seeds	kg dry matter/m³	N/A	-	x		
Timing of crop harvest	%		100			
January	%			x		
February	%			x		
March	%			x		
April	%			x		
May	%	0-100	100	x		
June	%			x		
July	%			x		
August	%	0-100	0	x		
September	%			x		
October	%			x		
November	%	0-100	0	x		
December	%			x		
Cost of crop at field before harvest	Euro/ton DM		400	x	*0*	Estimate
Nutrients, pesticides and work/fuel consumption	MJ/ha	35-50				
Direct energy consumption	GJ/ton DM					
Indirect energy consumption	GJ/ton DM					
Total energy consumption	GJ/ton DM			x		
Direct CO_2 emission	kg/ton DM					
Indirect CO_2 emission	kg/ton DM					
Total CO_2 emission	kg/ton DM			x		
Data validity						
Average field size	hectares/field					
Minimum cropping area	tons DM/season		0	x	*0*	Estimate

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Category:	Harvest					
Crop:	Saccharina Latissima			x		
Nomenclature | Sheet ID:	MacroAlgaeHarvester		271	x		
Country:	Denmark	DK	2			Insert customised figures in green cells
Date:						
Contact:	Jørgen Hinge, Technological Institute, jhi@teknologisk.dk					
Details					**Source**	**Remarks**
Biomass harvested	Saccharina Latissima from lines					
Short description/ID of machinery	Harvesting vessel with 30 tons storage			x		
Characteristics of equipment/machinery						
Description of machinery						
Contractor	Harvest is carried out by biomass growers or a contactor.					
Equipment can be applied for	Can be used for harvest of Macro Algae (other aplications after					
Manufacturer						
Website						
References	LGIT				**1**	
					2	
					3	
					4	
Specifications and data	**Units**	**Range**	**Figure used**		***Ref***	
Biomass input						
Description		S. Latissima on lines				
Dry matter content	% dry matter	13-15	14		*2*	
Biomass output						
Description	cm	0,1-2m	1,0		*2*	10-40cm width
Dry matter	% dry matter	16-18	17	x	*2*	
Bulk density	kg biomass/m^3		1.000			
Bulk density	kg dry matter/m^3	160-180	170	x	*2*	
Output-input ratio	**% DM output/input**		**95**	x	*4*	
Cost of basic machine	Euro	400.000-2.000.000	750.000		*3*	
Cost of dedicated equipment	Euro	500.000-700.000	600.000		*4*	
Total cost	Euro	900.000-2.700.000	1.350.000			
Net harvest capacity	ton DM/hour	0,75-1,2	0,9		*1*	
Efficiency	%	100	90,0		*4*	Efficiency on field
Gross harvest capacity on field	ton DM/hour		0,8			
Efficiency	%	100	100,0		*4*	Logistic set up - distance between fields
Gross harvest capacity - actual scenario	ton DM/hour		0,8			
Overall efficiency	%		90,0	x		
Harvesting costs	Euro/ton DM		491,83	x		Calculated considering also reference 1
Fuel consumption	l diesel/hour	50-65	57		*3*	
Cost of direct energy consumption	euro/l		0,78			1: Cost of diesel
Energy cost, euro/ton DM	euro/ton DM		53,02			Costs according to country code
Direct energy consumption	GJ/ton DM		2,44			
Indirect energy consumption	GJ/ton DM		1,70			Estimate
Total energy consumption	GJ/ton DM		4,15	x		
Direct CO_2 emission	kg CO_2/ton DM		214,51			
Indirect CO_2 emission	kg CO_2/ton DM		149,23			
Total CO_2 emission	kg CO_2/ton DM		363,74	x		
Security of supply	80 % probability that actual harvest is not delayed more than [-] of weeks		0	x	*4*	
Data validity						
Minimum harvest volume	tons DM/season	1.000-2.000	603	x	*4*	

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Category:	Unloading					
Crop:	Saccharina Latissima			x		
Nomenclature | Sheet ID:	MacroAlgaeUnloaderConveyor		471	x		
Country:	Denmark	DK	2			Insert customised figures in green cells
Date:						
Contact:	Jørgen Hinge, Technological Institute, jhi@teknologisk.dk					
Details					Source	Remarks
Biomass unloaded	S. Latissima in varying length/width					
Short description/ID of machinery/working procedure	Unloading of bulk harvesting vessel by crane and conveyer			x		
Characteristics of equipment/working procedure						
Description of equipment/working procedure	Biomass conveyed to drying device					
Contractor	Loading is carried out by the biorefinery or a contactor.					
Manufacturer	Numerous manufacturers					
Website	N/A					
References	LGIT				1	
					2	
	Hinge J. et al. (2013). Assessment.				3	
Specifications and data	**Units**	**Range**	**Figure used**		*Ref.*	
Biomass input						
Description	cm	0,1-2m	1			
Dry matter content	% dry matter	16-18	17		3	
Bulk density	kg biomass/m³		1.000			
Bulk density	kg dry matter/m³	160-180	170		3	
Biomass output						
Description		0,1-2m	1			
Dry matter	% dry matter	16-18	17	x	3	
Bulk density	kg biomass/m³		1.000			
Bulk density	kg dry matter/m³	160-180	170	x	3	
Output/input ratio	**% DM output/input**		**90,0**	x	3	
Cost of basic machinery	Euro		300.000		3	
Cost of dedicated equipment	Euro					
Total cost	Euro					
Net loading capacity	ton DM/hour		10,0		3	
Efficiency	%		75,0	x	3	
Gross transport capacity on field	ton DM/hour		7,5			
Loading costs	Euro/ton DM		13,00	x	3	
Fuel consumption	kWh/hour		50		3	
Cost of direct energy consumption	euro/kWh		0,11			3: Cost of electricity
Energy cost, euro/ton DM	euro/ton DM		0,72			Costs according to country code
Direct energy consumption	GJ/ton DM		0,02			
Indirect energy consumption	GJ/ton DM		0,03			
Total energy consumption	GJ/ton DM		0,05	x		
Direct CO_2 emission	kg CO_2/ton DM		0,02			
Indirect CO_2 emission	kg CO_2/ton DM		2,44			
Total CO_2 emission	kg CO_2/ton DM		2,46	x		
Security of supply	80 % probability that actual loading is not delayed more than [-] of weeks		0	x	3	
Data validity						
Minimum loading volume	tons DM/season		50	x	3	

eurobioref						
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This document is a data-sheet prepared to feed into the logistic model						
Category:	Pretreatment					
Crop:	Saccharina latissima			x		
Nomenclature | Sheet ID:	BrownalgaeDrying		671	x		
Country:	Denmark	DK	2			Insert customised figures in green cells
Date:						
Contact:	Jørgen Hinge, Technological Institute, jhi@teknologisk.dk					
Details					Source	**Remarks**
Biomass pretreatment	Brown algae dryer with separation of stones and other inorganic					
Short description/ID of machinery	Drum dryer with separation aggregate for stones and inorganic material			x		
Characteristics of equipment/machinery	Machinery is suitable for cleaning stabilization of wet algae material					
Description of machinery	Algae are dried in drum drier and stones and inorganic material is separated from the biomass					
Contractor	Drying/separation is carried out by staff of biorefinery or a contactor					
Manufacturer	Any type of wet biomass					
Website	Numerous manufacturers					
Type of biomass input						
References	xx; Personal communication				1	
					2	
					3	
	Hinge J. et al. (2013). Assessment.					
Specifications and data	**Units**	**Range**	**Figure used**		***Ref***	
Biomass input						
Description		0,1-2m	1			
Dry mattter content	% dry matter	16-18	17		3	
Bulk density	kg biomass/m³		1.000			
Bulk density	kg dry matter/m³	160-180	170		1	
Biomass output						
A. Brown Algea solid fraction	% extracted of DM		95			
Dry matter content	% dry matter		70		3	
Bulk density	kg biomass/m³		357		3	
Bulk density	kg dry matter/m³		250	x		
B. Stones and inorganic matter	% DM of input		5			
Description						
Stones and inorganic matter	% of volume		100			
Bulk density	kg/m³		1.000			
Bulk density	kg/m³		1.000			
Selling price of waste water	Euro/ton		0		1	
Output-input ratio	**% DM output/input**		**95**	x		
Cost of dryer and equipment	Euro		200.000		3	
Cost of buildings	Euro		0		3	
Total cost	Euro		200.000			
Net drying capacity	ton DM/hour	10-20	15,0		3	
Efficiency	%		80,0		3	
Gross drying capacity	ton DM/hour		12,0			
Efficiency	%		100,0		3	N/A
Gross drying capacity - actual scenario	ton oil/hour		12,0		1	
Overall effeciency	%		80,0	x		
Cost of drying	Euro/ton DM		475,9	x		
Value of press cake	Euro/ton DM		0,0			
Net cost of oil	Euro/ton DM		475,9	x		
Energy consumption	kWh/ton DM	3483	3483		3	
Cost of direct energy consumption	euro/kWh		0,11			3: Cost of electricity
Energy cost, euro/ton DM	euro/ton DM		374,01			Costs according to country code
Direct energy consumption	euro/ton oil		10,42			
Indirect energy consumption	euro/ton oil		0,01			
Total energy consumption	GJ/ton oil		10,43	x		
Direct CO_2 emission	kg CO_2/ton oil		914,25			
Indirect CO_2 emission	kg CO_2/ton oil		0,78			
Total CO_2 emission	kg CO_2/ton oil		915,03	x		
Security of supply	80 % probability that pretreatment is not delayed more than [-] of weeks		0	x	3	
Data validity						
Minimum amount	tons algae / season	1.000-2.000	200	x	3	

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This document is a data-sheet prepared to feed into the logistic model

Category:	Storage					
Crop:	Saccharina Latissima			x		
Nomenclature | Sheet ID:	Brown Algae Buffer Storage		1571	x		
Country:	Denmark	DK	2			
Date:						
Contact:	Jørgen Hinge, Technological Institute, jhi@teknologisk.dk					
Details					Source	Remarks
Biomass stored	S. Lattissima dried in drum drier					
Storage description - short	Brown Algae open central storage			x		
Type of storage/equipment	S. Lattissima dried uncovered on concrete floor					
Description of storage establishment and main charasteristics	Storages established centrally piling biomass. Storage height up to 10 m.					
Contractor	Storages are established centrally by unloading from drum dryer.					
Manufacturer	N/A					
References					1	
					2	
	Hinge J. et al. (2013). Assessment.				3	
Specifications and data	**Units**	**Range**	**Figure used**		*Ref.*	
Biomass input						
Description						
Dry matter content	% dry matter	0	70		3	
Bulk density	kg biomass/m³		357			
Bulk density	kg dry matter/m³	0	250		2	
Biomass output						
Description					3	
Month of biomass insertion	months	Jan, Feb, Mar,.....Dec	May		3	
Storage duration	number of months	1-12	3		3	
Dry matter content	% dry matter	50-80	69,8	Δx		A specific dry matter content according to months of storage
Bulk density	kg biomass/m³		358			
Bulk density	kg dry matter/m³		250	x	2	
Output/input ratio	% DM output/input		91,1	x	2	A specific output/input ratio is used for calculations according to month of biomass insertion and the duration of storage
Cost of basic storage facilities	Euro	0	0			
Cost of dedicated facilities	Euro	0	0			
Total cost	Euro	0	0			
Storage capacity	m³	500-99.999	10.000		3	**Maximum at each location**
Storage costs	Euro/ton DM		0,00	x		
Energy consumption	kWh/ton DM	35-50				
Cost of direct energy consumption	euro/kWh		0,11			3: Cost of electricity
Energy cost, euro/ton DM	euro/ton DM		0,00			Costs according to country code
Direct energy consumption	GJ/ton DM		0,00			
Indirect energy consumption	GJ/ton DM		0,00			
Total energy consumption	GJ/ton DM		0,00	x		
Direct CO_2 emission	kg CO_2/ton DM		0,00			
Indirect CO_2 emission	kg CO_2/ton DM		0,00			
Total CO_2 emission	kg CO_2/ton DM		0,00	x		
Security of supply	80 % probability that removal of storages is not delayed more than [-] of weeks		0		3	
Data validity						
Minimum storage volume	tons DM/season	1000-2000	100	x	3	