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Report

Development of area efficient and standardized structures for large-scale macroalgae cultivation

1D to 2D substrate deployment and facilitated monitoring

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ABSTRACT

This report is the result of a seven-week student summer project at MACROSEA.

For large scale seaweed cultivation to be a reality, the industry needs new cultivation methods that is designed for area efficiency, up-scalability and automation. In this report a new concept designed with these key criteria as a foundation are presented and compared to known concepts. Factors such as cultivation density and light absorption for the new concept is also calculated. The concept is taken from an idea to a proposed solution, but there is still a need for additional in-depth studies of the individual parts of the concept.

Another key component to the new concept is taking cultivation carrier ropes from a 1D form to 2D from. Meaning that during deployment and harvesting of the macroalgae the ropes is in a 1D form, however throughout the growth period the they act as in a 2D form by applying it to a structural-skeletons.

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1 Introduction

The Norwegian coast comprises six times that of the land area and is therefore one of Norway's greatest natural resources. HAV21 is the Norwegian strategy for research and development in the marine sector, and it recommends that the cultivation and harvesting of macroalgae is further developed and taken to an industrial scale. Macroalgae has a wide variety of uses ranging from biofuel to human and livestock consumption. MACROSEA is a project with a four-year duration, and is initiated to find the steps necessary to successfully cultivate macroalgae on an industrial scale along the Norwegian coast as described by HAV21. The goal is to facilitate predictable macroalgae cultivation and ensure a high-quality biomass. To accomplish this, new research in all the steps of the cultivation process is needed, from large scale seeding to industrial harvesting. The project is a collaboration between SINTEF Ocean and multiple research and industry partners spread along the Norwegian coast. The macroalgae industry is to this day highly labour intensive and depends mainly on manual tools that are not optimized for the job. There is therefore a need for new industrial tools that can help the industry to become more efficient and at the same time ensure a premium quality on the end product.

Today macroalgae is for the most part cultivated on what is called a 1D substrate, i.e. ropes. 1D substrates haves proven to be easy to handle and provide high yield of biomass, though they are not particularly area efficient. Seaweed Energy Solutions states that on average they have 1 meter 1D substrate pr. square meter in their cultivation fields (Funderud, 2017). This low area efficiency has led some producers to look at ways of cultivating macroalgae on a 2D substrate. 2D substrates can be produced in multiple ways such as sheets or nets. One of the producers that have accomplished cultivation on a 2D substrate is AT-SEA/SIOEN. They use a 10 by 3.2-meter sheet that can yield up to 14 kg/m^2 of *Saccharina latissima,* which shows that a 2D substrate can have good yield pr. area (Groenendaal, 2017). The main challenges with a 2D substrate is handling during deployment and harvesting and cultivating the spores on a large substrate, which has proven difficult. One solution to these problems is that the substrate is in a 1D form during deployment and harvesting, and in a 2D form during the growth period. Henrikke Dybvik, a former summer intern at the MACROSEA project wrote the report "Concept development for macroalgae seeding, deployment and harvesting". In this report, she proposed ways of turning 1D substrate into 2D form, such as knitting a net. She concluded that it would be difficult to make a net from 1D substrate without the knitting equipment destroying some of the spore seeds on the cultivation ropes. Other difficulties may be that the net could get entangled during the growth period. As a solution to these problems this report looks at the possibility of cultivating on a structure that permits a 1D to 2D transition, and at the same time optimized the area usage of the production.

1.1 State-of-the-art 2017

To be able to understand the difficulties and limitations of today's cultivation methods, it is natural to look at some of the leading contributors to large scale macroalgae cultivation. In 2017 the most common way to apply macroalgae seed to carrier ropes is by cultivating spores on thin ropes in a laboratory, then spinning it around a larger carrier rope. Some companies are experimenting with direct "spraying" of spores on to the carrier rope, but with warrying results.

1.1.1 Seaweed Energy solutions

Seaweed Energy Solution was established in 2006 and is based in Trondheim, Norway. Their vision is to enable large scale cultivation of macroalgae (SES, 2017). Their production consists mainly of horizontal carrier ropes, at shallow depths. To this date, they have a production at about 30 metric ton biomass per hectare, and an average of 1 meter carrier rope per square meter (Funderud, 2017). Figure 1 shows one of their production sites.

Figure 1 - Seaweed Energy solutions production site (image from www.seaweedenergysolutions.com)

1.1.2 Seaweed AS

Seaweed AS is a company based in Bulandet on the west coast of Norway, they cultivate macroalgae for human consumption. Seaweed AS has in collaboration with Værlandet fiskeredskap developed the cultivation system BULAND 10. This system has a cultivation area of 1 hectare and a total of 2500 meter of carrier rope (Væerlandetfiskeredskap, 2017). The system consists of horizontal carrier rope in tension by an external rope rig/frame, as shown in Figure 2. The system can be enlarged by joining multiple rope rigs together.

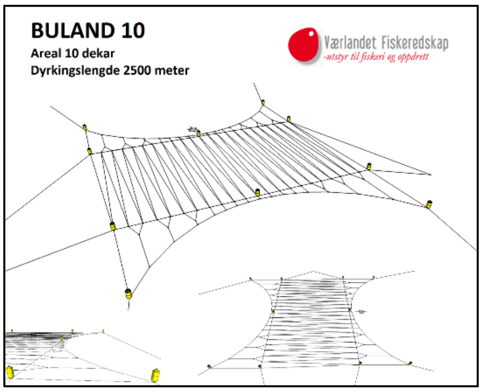

Figure 2 - Seaweed AS cultivation system Buland 10. Developed in collaboration with Værlandet fiskeredskap (image from vaerlandetfiskeredskap.no)

1.1.3 AT-Sea/SIOEN

Algaesheet is a spin-off from the European project AT-Sea and is produced by the Belgian company SIOEN. The system consists of 10 by 3.2 metre sheets connected to form a 100-metre-long unit, as illustrated in Figure 3. They have reported that their system has yielded up to 14 kg/m^2 of *S. Latissima* on winter crops on the coast of Ireland.

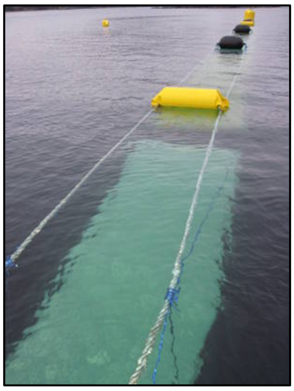

Figure 3 - Algaesheet from At-Sea/SIOEN (image from ecn.nl)

2 Concept development

In this report a new cultivation concept for macroalgae is developed. The main inspiration for the cultivation systems proposed are weather buoys and fish farming equipment. Both have very distinct advantages that can be utilized in large scale macroalgae cultivation.

The weather buoys are floating structures often with a single mooring point, permitting easy deployment and moving. Weather buoys are also self-sustaining and are therefore able to collect and transmit data in real-time over long durations. Such features are ideal for macroalgae production. The ability to collect weather and growth data of algae can give a better understanding of the parameters governing a good biomass as well as it makes it easier to monitor multiple production units from a single communication central.

Commercial fish cages are a well developed and tested concept. The HDPE (High Density Polyethylene) structure has high strength, is not affected by corrosion and handles the hydrodynamic strains well. This makes it an ideal inspiration for a new large-scale macroalgae cultivation system. The mooring system in modern fish farms also permits easy scaling.

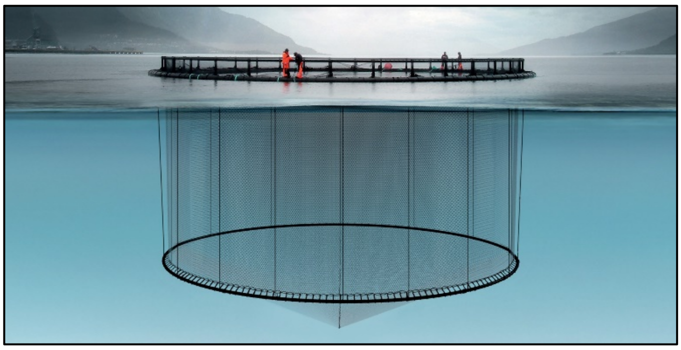

Figure 5 - Traditional HDPE fish cage from AKVA Group (image from www.akvagroup.com)

Figure 4 - National Data Buoy Centre operated 3-meter discus buoy for taking weather and marine observations (image from www.ndbc.noaa.gov)

2.1 Design criterions

If the new cultivation is to be a viable solution it must perform according to some design criteria. There are multiple design criteria that have to be taken in to consideration for a new cultivation system, but the most important for sustainable biomass production and area optimization is taken into consideration in this report.

2.1.1 Light dependency of macroalgae

The growth of macroalgae is highly light dependent, and it is therefore of the outmost importance that a new cultivation system does not limit the algae’s access to light. The rate of photosynthesis in macroalgae increases with increasing PAR irradiance. For a certain level of irradiance the photosynthetic rate will be saturated, and further increases in irradiance will have no effect. In the paper “Modelling the cultivation and bioremediation potential of the kelp *S. latissima* in close proximity to an exposed salmon farm in Norway” by Broch, et al., 2013 it is proposed that the irradiance for maximal photosynthetic rate for *S. latissima* is $\lambda_{min} = 90\ \mu mol/m^2 s$. There is some uncertainty regarding this lower saturation value, but in this report, I have chosen to regard this as the lower PAR limit for saturation.

2.1.2 Area efficiency

In Norway macroalgae cultivation is area quota based. Therefore, it is important to get as high a yield per hectare as possible. It is believed that one hectare has enough nutrients to yield from 100 to 300-ton biomass. Today the average production is around 30 ton per hectare. A new cultivation system should be able to utilize more of the potential.

2.1.3 Automation

Automation is a key component to develop large scale macroalgae cultivation, this is why it is important that a new cultivation system has been designed with automation in mind. An ideal situation is if all of the steps in the cultivation process (mainly deployment and harvesting) is automated. Another form of automation is monitoring of growth and the surrounding environment. Such monitoring can ensure that deployment and harvesting happens at the right condition.

2.1.4 Up-scalability

If large scale seaweed cultivation is to be a reality, a new cultivation concept should be easy to up-scale. This means for example that the work needed to deploy one unit should not differ much from deploying 4 units. Another important feature to allow up-scaling is standardization. Equipment used on one unit at one location should be applicable at another unit at another location.

2.2 Primary design concepts

There are two main shapes taken in to consideration in this report, a disc shape and a conical frustum. Square and rectangular shapes are not taken in to consideration even though they are more area efficient, since they have severe strength disadvantages compared to circular shapes.

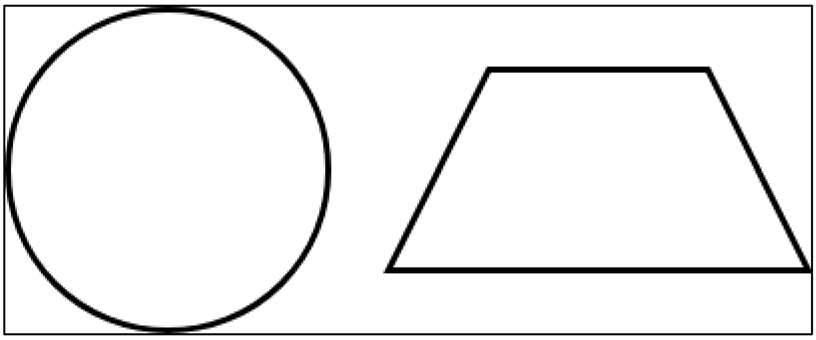

Figure 6 - Left: top view of disc shape. Right: Side view of conical frustum shape

The disc shape acts as a 2D planar structure and the conical frustum is a 3D structure. Both shapes are circular in nature, to insure high strength (no stress concentrations in corners) and good area utilization. Another benefit of using round tube construction is that it is possible to utilize already mature materials and construction techniques from the fish farming industry. The conical shape can angle its sides to optimize the sun exposure during the growth period. For this to be a viable solution the conical structure must be able to rotate in the water to ensure that all sides get the same amount of exposure. Another key element of the design concepts is the ability to deploy the substrate in an 1D form, grow in a 2D form then back to 1D for harvesting. To accomplish this the proposal in the report is to “wrap” the 1D substrate on the frame structure, thus turning it in to a 2D form. When harvesting, the substrate is unwound of the frame structure. Another advantage of wrapping the 1D substrate on a frame structure is that substrate is evenly spaced and under constant tension, this will then prohibit entanglement of the substrates.

2.3 Horizontal vs. optimized angled cultivation system

The hypothesis is that conical frustum shaped cultivation system is beneficially over a normal horizontal cultivation system when it comes to light exposure. This hypothesis is based on that the sun light rarely acts directly downwards on-to the water surface, this causing it to refract and change its angle of attack as it enters the water, as explained by Snell's law (eq. 1). With this refraction in mind, a slanted surface should be able to absorb more of the light than one that is horizontal. As explained in section 2.2, the conical frustum shaped cultivation system is to be rotating with a constant speed (for example one rotation per day), ensuring that all the kelp is exposed to the same amount of sun light through a given time period.

Table 1 - Summary of inputs, variables and parameters used in light calculations

Symbol	Type	Unit/Value	Description
θ_i	Input	°	Angle between light source and horizon
θ_t	Variable	°	Reflected angle
$\theta_{surf.}$	Input	°	Side angel of conical frustum
n_1	Parameter	1.000293	Refractive index, air
n_2	Parameter	1.333	Refractive index, Water at 20°C
R_s	Variable	-	Reflectance of s-polarized light on a non-metallic media
R_p	Variable	-	Reflectance of p-polarized light on a non-metallic media
R	Variable	-	Total reflectance
$\lambda_{dir.r}$	Variable	$\mu mol/m^2s$	Direct radiation PAR (Photosynthetically Active Radiation)
$\lambda_{def.r}$	Variable	$\mu mol/m^2s$	Defuse radiation PAR
$\lambda_\perp$	Variable	$\mu mol/m^2s$	Total PAR on a plane normal to sun
$\lambda'_\perp$	Variable	$\mu mol/m^2\,s$	Total PAR on a plane normal to sun, reduce by reflectance
$\bar{\lambda}'_\parallel$	Variable	$\mu mol/m^2s$	Average PAR on plane parallel to the horizon, reduced by reflectance
$\bar{\lambda}_\measuredangle$	Variable	$\mu mol/m^2s$	Average PAR on plane angled towards light source.
P	Parameter	$1.0\ mg/m^3$	Chlorophyll concentration
a_{cDOM}	Parameter	$0.2\,m^{-1}$	cDOM absorption
$E_{PAR}(i)$	Variable	$\mu mol/m^2s$	PAR at a given depth
dz	Input	m	Depth

2.3.1 Average sun height

To calculate the average sun height, the MATLAB script sunelev[1] was used. This script returns the angle between the horizon and the sun at a given date, time and latitude. In these calculations, the sun angle was obtained with a one week interval starting 21.11.2016 and ending 29.05.2017, i.e., 28 weeks in total. Trondheim was used as an example location with its latitudinal placement of 63.4297[2]. This resulted in an average sun height of $\theta_i = 12.635°$.

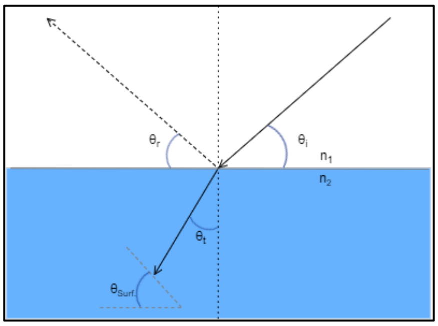

Figure 7 - Illustration of angles due to refraction

2.3.2 Refraction of sun rays

As stated in section 2.3 it is assumed that Snell's law (eq. 1) of refraction applies and that both the air and the water are homogenous. With the sun height θ_i, calculated in section 2.3.1 and the refractive indices presented in Table 1, the resulting refraction angle is $\theta_t = 47.07°$. The resulting angles are illustrated in Figure 7.

$$\frac{\sin(90° - \theta_i)}{\sin(\theta_t)} = \frac{n_2}{n_1} \tag{1}$$

2.3.3 Reflectivity of sun rays

Using Fresnel equation and assuming that the light from the sun in unpolarised and both the water and the air is homogenous we are able calculate the amount of light reflected away from water surface (Vaughan, 2014). This reflection factor can then be used as a reduction factor for the PAR of the light passing through the water surface. Fresnel equation distinguishes between s- and p-polarised light as shown in eq. 2 and 3, but by assuming that the light still is unpolarised after passing through water, we get the total reflectance, as shown in eq. 4. Using the angle θ_i and θ_t described in section 2.3.1 and 2.3.2 respectively, and the refractive indices presented in Table 1, the resulting reflectance is at $R = 26.7\%$.

$$R_s = \left|\frac{n_1 \cos(90° - \theta_i) - n_2 \cos(\theta_t)}{n_1 \cos(90° - \theta_i) + n_2 \cos(\theta_t)}\right|^2 \tag{2}$$

$$R_p = \left|\frac{n_1 \cos(\theta_t) - n_2 \cos(90° - \theta_i)}{n_1 \cos(\theta_t) + n_2 \cos(90° - \theta_i)}\right|^2 \tag{3}$$

$$R = \frac{1}{2}\left(R_s + R_p\right) \tag{4}$$

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[1] The script was provided by Morten Omholt Alver at SINTEF Ocean

[2] WGS84, decimal form

2.3.4 Calculating the average radiation on the surface of a rotating conical frustum

By using a MATLAB script[3] based on the work of Bird, 1984 it is possible to calculate both the direct and diffuse PAR at any given sun height. Given the angle θ_i from section 2.3.1, the script retuned a direct and a diffuse PAR of $\lambda_{\perp,dir.r} = 540.2\ \mu mol/m^2 s$ and $\lambda_{def.r} = 313.0\ \mu mol/m^2 s$, respectively. These values are for a surface normal to the sun, by multiplying the direct PAR by the cosine of the sun angle and adding the diffuse PAR, we obtain the total PAR-value to a horizontal surface, $\lambda_{\parallel,total} = 431.2\ \mu mol/m^2 s$. When reducing the $\lambda_{\perp}$ by the reflectivity factor obtained in section 2.3.3, we get the maximal PAR-value after reflection, $\lambda'_{\perp,total} = 625.2\ \mu mol/m^2 s$[4]. This again gives the average PAR of a surface parallel to the horizon while under-water $\bar{\lambda}'_{\parallel,total} = 499.0\ \mu mol/m^2 s$.

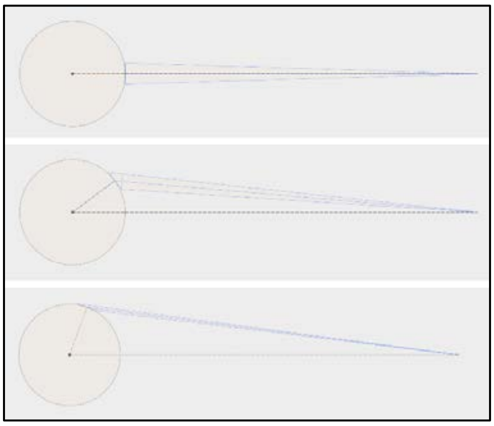

Figure 8 - Illustration of radiation on plane as it rotates away from light source.

Figure 11 shows the average PAR $\bar{\lambda}_{\measuredangle}$ as a function of plane angle $\theta_{surf.}$. From this we see that the optimum plane angle is $\theta_{surf.} \approx 47°$ relative to the horizon (for a conical frustum shaped cultivation system), which gives the highest direct PAR in the given time period. This angle results in maximal PAR of $\lambda_{\measuredangle,max} = 625.2\ \mu mol/m^2 s$ (adjusted for reflection). A comparison between different planar orientation on a weekly basis is presented in Figure 10.

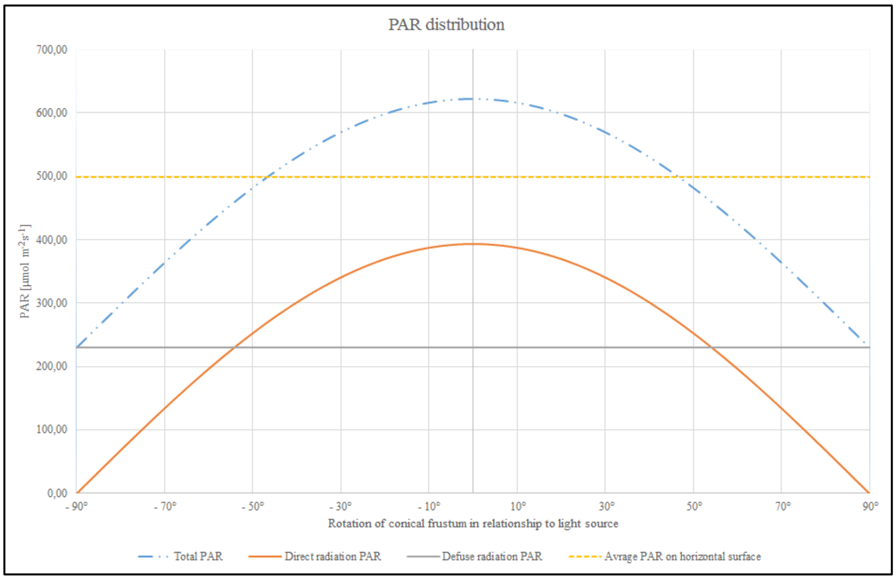

Figure 9 - PAR distribution as a conical frustum plant rotates, versus normal horizontal cultivation plant.

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[3] The MATLAB script was provided by Morten Omholt Alver at SINTEF Ocean

[4] 63.3% Direct PAR and 36.7% diffuse PAR

By assuming that the cultivation plant rotates with a constant speed, $\bar{\lambda}_{\measuredangle}$ is an average PAR of all surfaces as the plant is subjected to light from one side. The diffuse radiation is equal through the circumference, and only the side that is facing the light source is subjected to direct PAR as well as defuse. The amount of direct PAR decreases as the plant rotates away from the light source, as shown in Figure 8. To calculate this reduction of direct PAR, the reduction of the light opening is calculated for every degree of rotation and then multiplied with the direct PAR at zero rotation (as shown in Figure 8). This gives an average of $\bar{\lambda}_{\measuredangle} = 355.0\ \mu mol/m^2 s$, which is 28.8% lower light exposure than that of a horizontal surface $\bar{\lambda}'_{\parallel}$. The distribution of PAR as the plant rotates is presented in Figure 9.

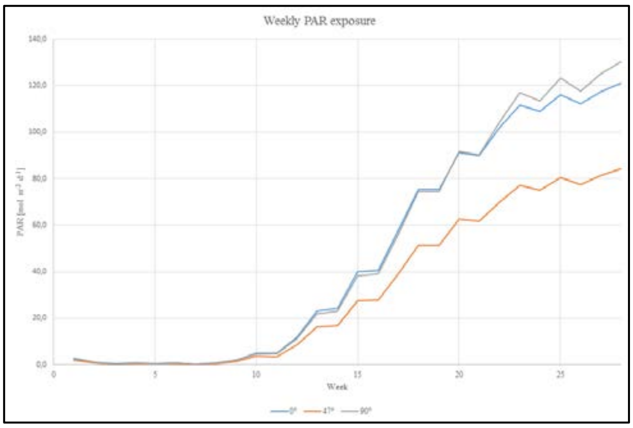


Figure 10 – Comparison of planar orientations on a weekly basis

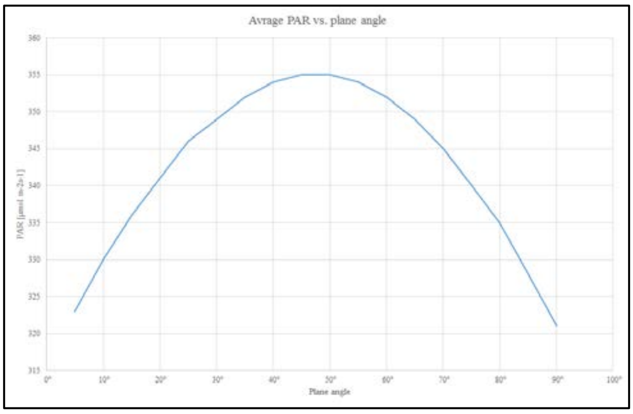


Figure 11 - Average PAR as a function of plane angel $\theta_{surf.}$

2.3.5 PAR reduction due to depth

In reality the PAR decreases with every meter of depth. To correct for this, equation 5 is used. This equation corrects the PAR relative to the chlorophyll concentration and the cDOM absorption in the water. The chlorophyll concentration and cDOM absorption varies from season to season and between locations. To simplify, the somewhat arbitrary values presented in table 1 is used in these calculations. The method and equation for PAR absorption was presented in the paper "A spectrally-resolved light propagation model for aquatic systems: Steps toward parameterizing primary production" by Alver, et al., 2014. By applying equation 5 to $\bar{\lambda}_{\measuredangle}$we get a distribution as shown in Figure 12. In this figure a lower PAR limit as described in section 2.1.1 is added. Over this limit, it is assumed that the photosynthetic activity is fully saturated. Under this limit, the growth of the algae can be limited.

$$E_{PAR}(i) = E_{PAR}(i-1) \cdot exp\big(-dz(0.04 + a_{cDOM} + 0.0088P + 0.054P^{0.667})\big) \qquad (5)$$

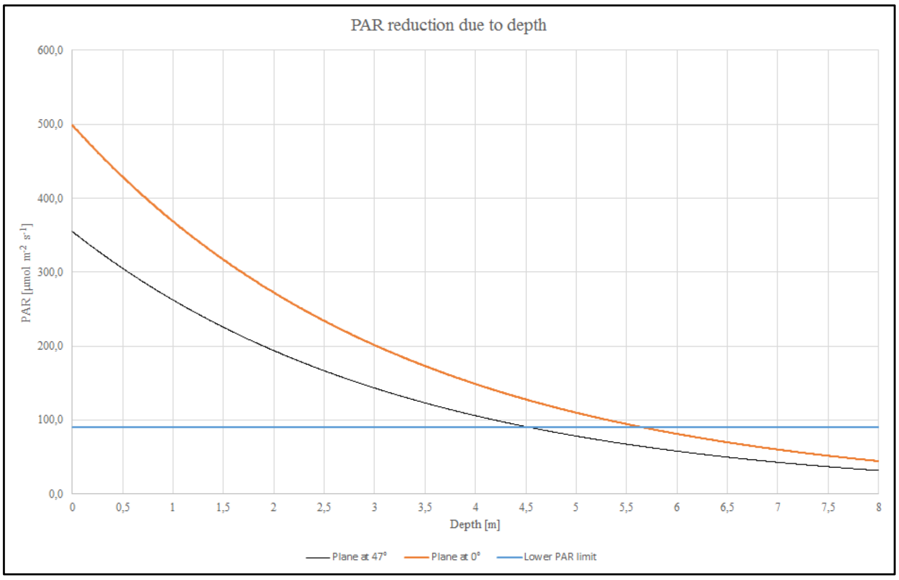


Figure 12 - Reduction of PAR as a function of depth

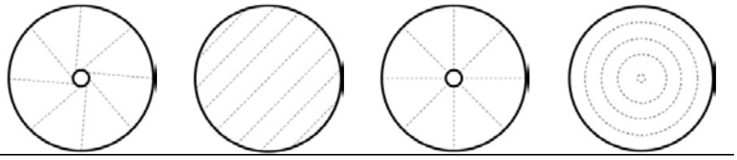
2.3.6 Choice of geometry

When comparing the results in section 2.3.1 through 2.3.5, it is clearly that a conical frustum shape has its disadvantages when it comes to average light exposure. If a conical frustum is to be beneficially the average PAR, $\bar{\lambda}_{\measuredangle}$ should to be greater than the $\bar{\lambda}'_{\parallel}$. But as stated in section 2.3.4, the conical frustum results in a 29% degrees of average PAR when compared to a horizontal plane. Even though the average of $\bar{\lambda}_{\measuredangle} = 354.06\ \mu mol/m^2\, s$ is well over the limit of λ_{min} stated in section 2.1.1. Another limiting factor is illustrated in Figure 12, at depths greater than 4.5 m the PAR is lower than that for λ_{min} for a conical cultivation plant. With these two factors taken in to consideration, the size of the cultivation plant is somewhat limited, due to the optimal cone angle $\theta_{surf} = 47°$ and the maximum depth. Figure 10 illustrates that it is possible to change the θ_{surf}, to a lower one for example down to 25°, with only a small loss in average PAR. By reducing the angle to 25° and a maximal depth of 4.5 metre (larges depth with full PAR saturation, figure 12), we get a maximal diameter of 24 m (area of 463.8 m^2). Nevertheless, this shows that it is most reasonable to choose a disc shape cultivation over a conical one, both when light and structural simplicity is taken in to consideration.

2.4 Area optimizing and carrier rope estimations

As stated in section 2.2 the 1D substrate is to be wrapped around the frame structure of the cultivation plant. There are multiple wrapping possibilities but the most promising are presented in Table 2. The main challenges with the different wraps is both the area optimizing and the practical aspects. For comparison, the outer frame ring has a diameter of 25 meters, and for those with an inner ring that has a dimeter of 3.5 meters.

Table 2 - Wrapping pattern



Type	Slanted outward	Slanted	Outward	Helix spiral
Outer Ø.	25 m	25 m	25 m	25 m
Inner Ø.	3.5 m	-	3.5 m	-
Min. carrier rope spacing	0.15 m	0.60 m	0.14 m	0.60 m
Max. carrier rope spacing	0.98 m	-	0.98 m	-
Total cultivation length	896 m	815 m	860 m	791 m
Projected area	491 m^2	491 m^2	491 m^2	491 m^2

From Table 2 we see that a slanted outwards wrap gives the longest possible carrier rope, given a minimum spacing of 0.15 m. This wrap in combination with a centre ring, ensures that the unsupported length of each portion of the carrier rope is minimised to the radii of the structure, in comparison the carrier rope on the slanted wrap has an unsupported length equal to the diameter of the structure. For this reason, the slanted outward wrap is the most logical wrap style to move forwards with.

2.5 Structural development

2.5.1 Frame structure

The main structure of the cultivation plant consists of two rings both made from 400 mm o.d. HDPE tube. These rings are held to gether by three 300 mm o.d. HDPE tubes normal to the wrapping angle of the carrier rope. This angle is to minimise the radial forces on the tubes as they absorb the torotion as a result of the cultivation rope tension. It is envisioned that the structure is ultrasonicly welded together, which will give a solid bond between the parts. HDPE is an ideal material for this purpose with its non-corrosive nature, high strength, ~nautral buoyancy in water and ease of fabrications, this is some of the reasons why it has been used in the fish cultivation industry for years. Other materials may also be considered. In this report ther has been no structural analysis conducted, it is therefore not possible at this time to tell if the structure has suffisient strength. Espcially the 300 o.d. tubes are prone to buckling as they have a high aspect ratio and may be subjected to compression forces, and therefore it is recommended that a nonlinear bucling analysis is conducted.

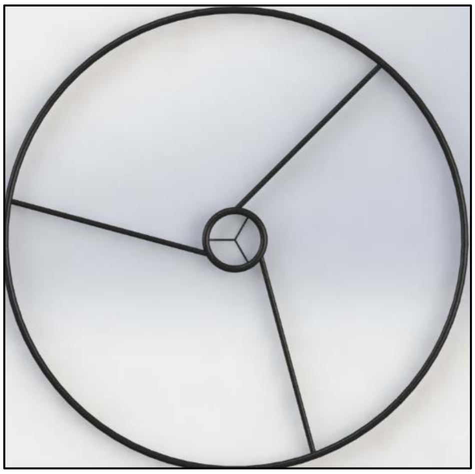


Figure 13 - Top view of frame structure

2.5.2 Cultivation rope attachment

To safely attach the carrier rope to the frame-structure a "clam cleat" inspired end piece is utilized. A clam cleat works by friction. The rope is wedged between two oblique sides with raised slots angled in such a way that it locks the rope in the tension direction. To release the rope, it is as simple as pulling it in the opposite direction of the locking direction.

Figure 14 - Clam cleat (image from www.svb24.com)

By locking the carrier rope at every turn, it limits the risk of unwinding, if it were to break at some point. In addition to the locking of the rope, the carrier rope is divided in to 4 separate pieces. This ensures that if one of the ropes were to fail the whole structure will not fail, it also helps to stabilize the structure when the carrier rope is applied, since this permits applying it in segments. Both the outer turn and the inner turn of the carrier rope is locked in the same manner.

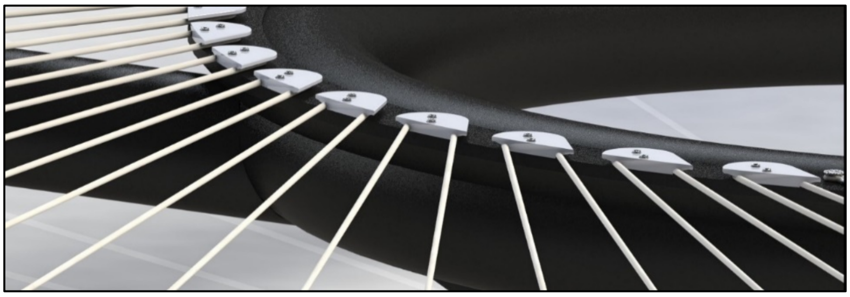


Figure 15 - The inner clam cleat locking system

2.5.3 Automated deployment and harvesting tool

The new cultivation concept is designed with deployment and harvesting in mind. To achieve automated deployment and harvesting, the idea is to use a separate structure that is deployed from a service vessel then mounted on the frame of the plant, come deployment or harvesting. It utilizes the round shape of the plant and is designed to slide on its circumference. While the tool is sliding on the circumference of the two main frames a “robot” slides back-and-forward deploying the carrier rope.

The tool is designed only to be deployed during deployment and harvesting. It is to be lowered down from a service vessel. To ease the mounting of the tool, it is fitted with “gripping-arms” at both ends, these also holds it in place during operation. If deployment is proven to be hard even with the use of the “gripping-arms” at the ends of the boom, it is possible to fit the boom with small thrusters at each end that can guide it towards some sort of guidance system on the cultivation plant (ex. using RFID technology).

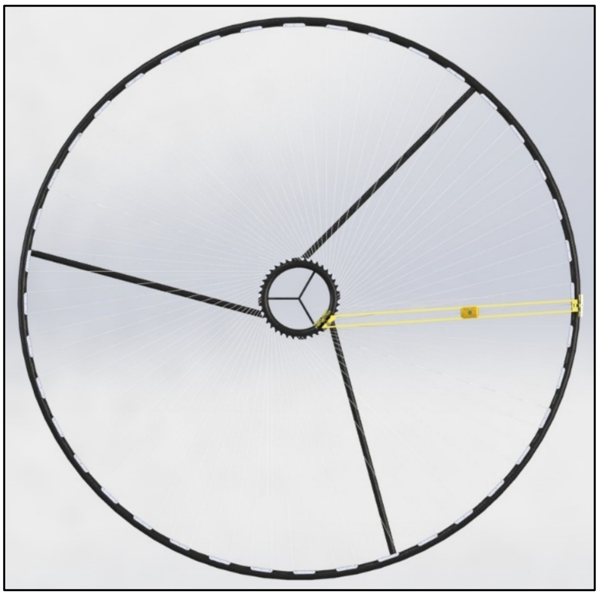


Figure 16- Top view of plant with automated deployment/harvesting tool attached

The tool can be driven around the circumference by small motors at each end of the boom. For this system to work it is important that the deployment/harvesting tool is aware of it position on the frame at all times. This to ensure that the carrier rope is correctly attached to the attachment points as described in section 2.5.2. This is also possible by the use if RFID technology by spacing a certain number of these around the subconference of both the inner and outer ring, the tool will be able to know its location relative to the plant (as a rotary encoder).

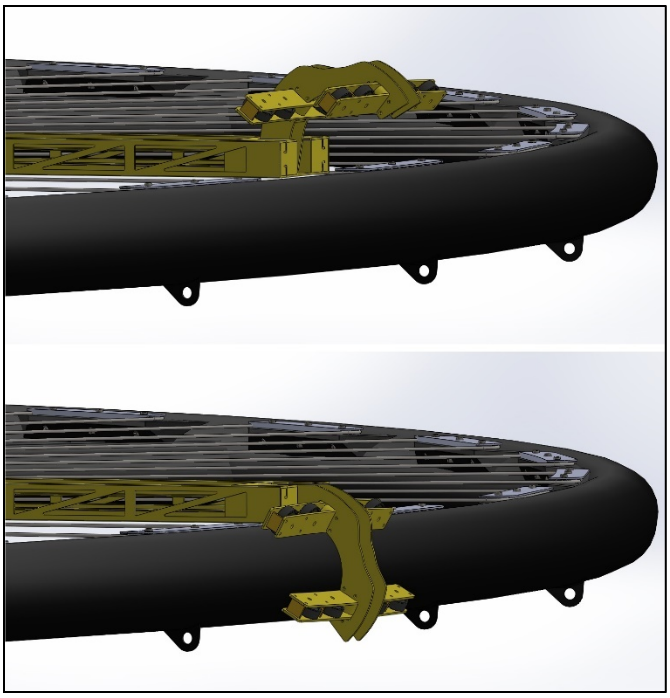


Figure 17 - Clamping of deployment/harvesting tool to main structure

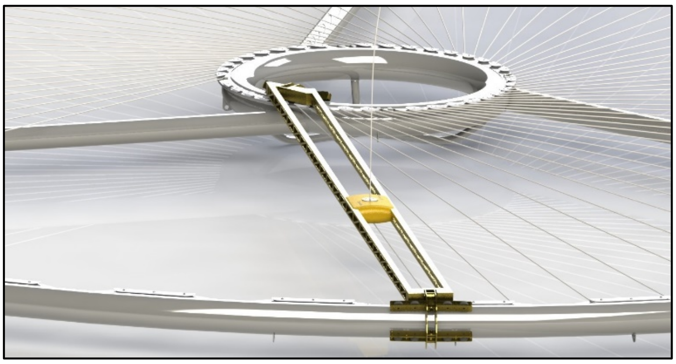


Figure 18 - Deployment/harvesting robot

2.5.4 Mooring

The mooring system is inspired by that commonly used in fish cultivation industry. It consists of a rope grid which the cultivation plant is connected to. This rope grid it then anchored to the seabed. The advantage of this mooring system is that it permits easy scaling. Also, the difference in installation cost between for example a 2x2 system versus a 2x3 is minimal.

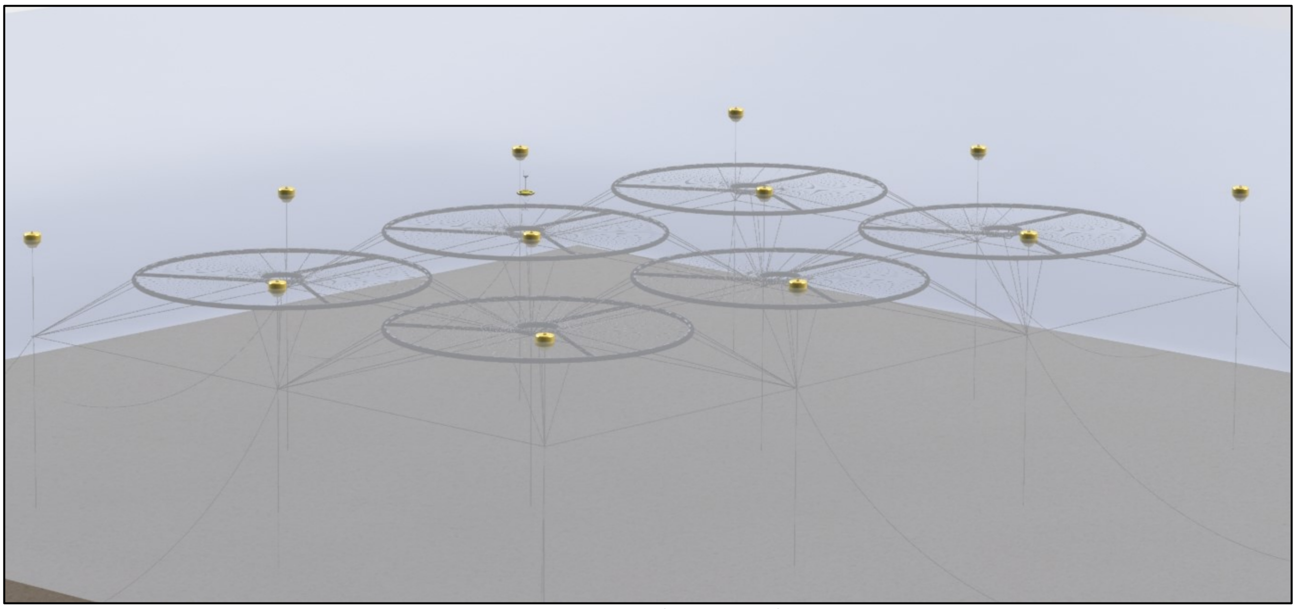


Figure 19 - Mooring system for a 3x2 configuration

2.5.5 Data collection buoy

In the new cultivation concept, one or multiple units can be fitted with a data collection buoy. This buoy can house sensors to collect data about the environment in which the seaweed grows. The buoy is fitted with batterie's and solar panels, which makes it self-sustainable and able to relay information back to HQ in real-time. The buoy has a single-point mooring system and is anchored to the middle of the cultivation frame. This monitoring platform has a huge potential of different monitoring parameters, under I have listed-up a few examples.

- Air temperature
- Water temperature at different depths
- Wind direction and velocity
- Water current direction and velocity
- PAR measurement at surface and at different depths (can be utilized to calculate biomass)
- Spectral measurements
- Wave height and period
- Macroalgae grow data
- Mooring tension forces
- Conductivity

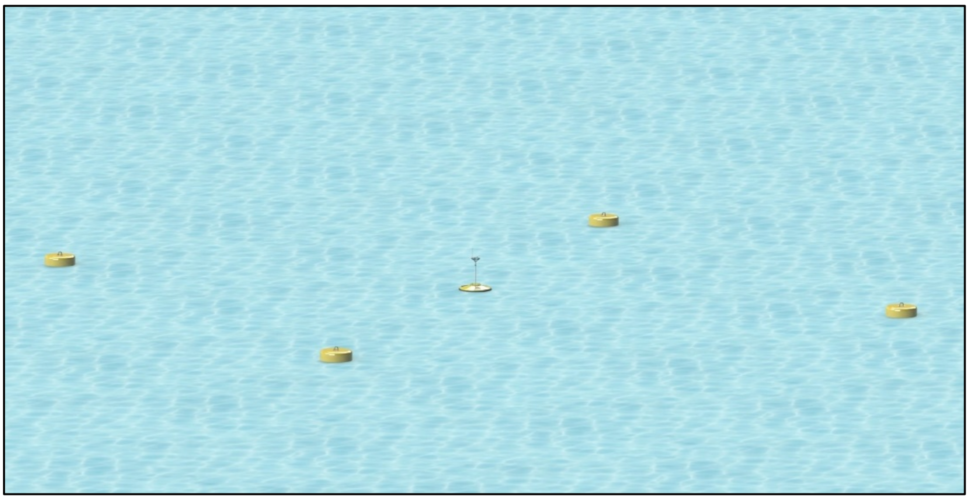


Figure 20 - Data collection buoy

3 Discussion

By comparing the new cultivation system to already existing systems it is possible to get an overview of its full potential. In table 3 a presentation of the example plant versus the previous mentioned systems is presented.

Table 3 - Comparison of new concept versus established concepts

	New concept	SES	Buland 10	SIOEN/Algaesheet
Cultivation length per unit	872 m	~3000 m	2500 m	10x3.2 m
Number of units	6	1	1	9
Total cultivation length	5 232 m	~3000 m	2500 m	10 m
Plant size	90x60 m	100x100 m	100x100 m	100x3,2
Area used	0.54 ha	1.00 ha	1.00 ha	~0.064 ha
Potential yield per	8-10 kg/m	8-10 kg/m	8-10 kg/m	14 kg/m
Potential yield	~41.9-52.3 ton	~30 ton	~20-25 ton	4.0 ton
Production density	~96.8 ton/ha	~30 ton/ha	~25 ton/ha	~62.5 ton/ha

From this comparison, it is clearly that the new concept has a huge potential yield. But some of the assumptions that can limit this potential yield is the fact that it is unsure if macroalgae is able to grow in such close proximity as described in section 2.4. Suggestions to how to study their ability to grow in close proximity will be presented in the section future work. Figure 22 is a comparison of the areal usage of the different cultivation concept are presented. The new concept has actual cultivation area of ~ 0.3 Ha (six units).

The calculations of light properties for the two concepts (section 2.3) are under ideal light and weather conditions. Some of the limitations and assumptions in these calculations is that the water surface is perfectly calm, so that Snell's law applies, and that there is a cloudless atmosphere through the period. It is also assumed that the direct radiation PAR-value angle of attack changes together with the light direction after passing through the water surface due to refraction. Because of these assumptions, the result of these calculations is to be considered as estimates.

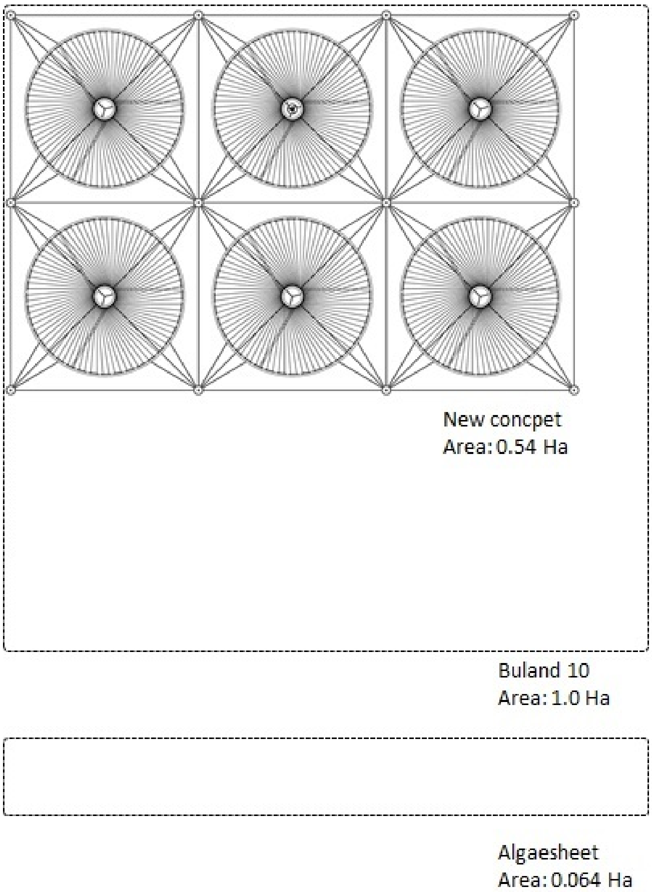


Figure 21 - Area comparison

The seeding method of the cultivation rope can have an impact of the performance/features of the deployment/harvesting robot. In my opinion it would be beneficiary if the seeds (spores) were applied directly to the rope when passing through the robot. This will then ensure that none of seeds are scrapped-off or damage when the rope is fed from the service vessel and down-and-through the robot. Another benefit with direct seeding versus spinning of seeding rope on to carrier rope, is that when it comes to harvesting the seeding rope will not be in the way of the harvesting.

The actual size of the unit it in this report somewhat arbitrary. A diameter of 25 metre has been used as an example size, and seems to be a good baseline for further development. In reality the size of one unit is largely based on the material used and its shape, and to find the optimal/maximal size an in-depth structural analysis is necessary.

4 Considerations and further work

There are still multiple factors that should be checked out before this new cultivation system can be taken to market. Here are some of the factors that I see as essential:

- **The strength of the frame:** It is important that there is conducted some sort of FEA/FEM analysis on the structure. This is to find eventual weak spots that needs additional reinforcement and to see if the frame has sufficient flexibility and strength. As mentioned in section 2.5.1 the 300 mm o.d. tubes have a high aspect ratio and there are therefore need for some sort of buckling test.
- **The carrier rope attachment points:** need additional development to ensure that they apply enough friction to hold the carrier rope in place.
- **The deployment/harvesting tool need to be further developed:** at this stage the deployment-/harvesting tool is at a concept stage and there is need for an in-depth study of the features necessary to make the tool a viable solution.
- **The mooring system:** and mooring anchoring points (on cultivation frame) need further testing to ensure sufficient strength.
- **Tank experiments:** to see if the system has sufficient strength towards hydrodynamic forces.
- **Biological studies:** A major part of the feasibility of this new cultivation concept is weighted on macroalgae ability to grow in close proximity and yield god biomass at the same time. To my knowledge there has been no successful studies at this subject. It is therefore important that such studies are conducted before this cultivation concept is further develop. A possible way of doing such a study is to use the test system illustrated in figure 23.

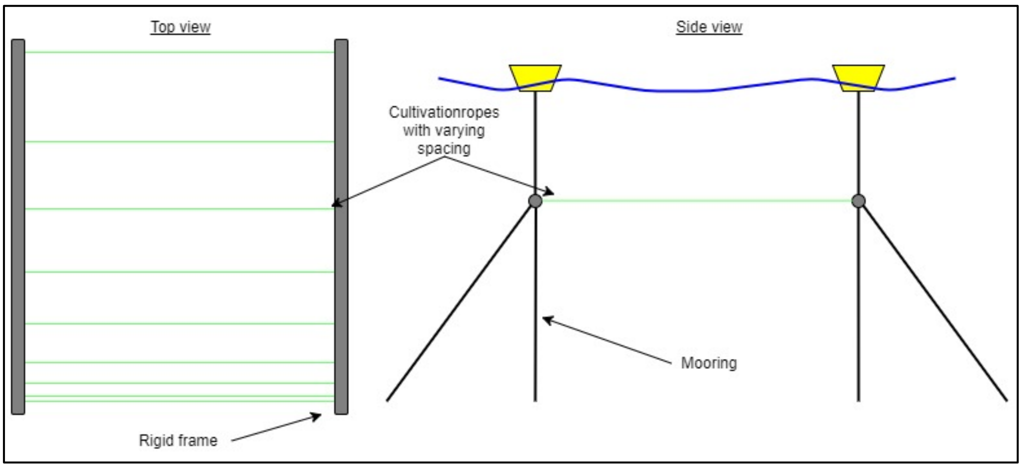


Figure 22 – Close proximity cultivation test setup

5 Conclusion

The new cultivation concept presented in this report has promising results, when compared to the criterions proposed in section 2.1. There are still need for further development and in-depth studies, but as is I regard it as a fully plausible solution. This report can also conclude with that calculations shows that a conical light optimized structure will not be beneficial over a horizontal plane structure.

With this new concept, we are looking at a cultivation density increase of 105-117% when comparing to already existing cultivation methods. But there are still need for biological studies to verify that that the calculations in this report is an accurate representation of the true potential from macroalgae cultivation.

It is decided that the new cultivation system is to be called: MACROSEA – SPOKe. SPOKe is an acronym for Standardized Production of Kelp.

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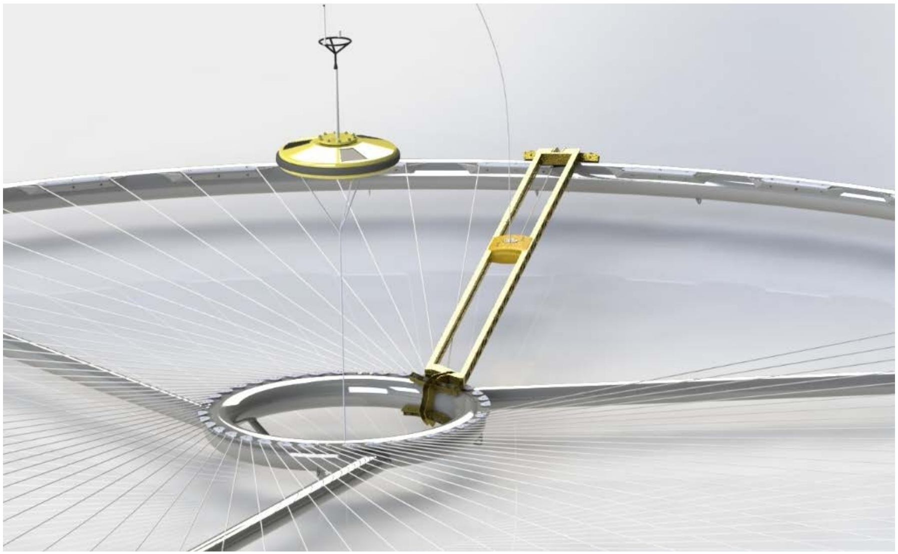
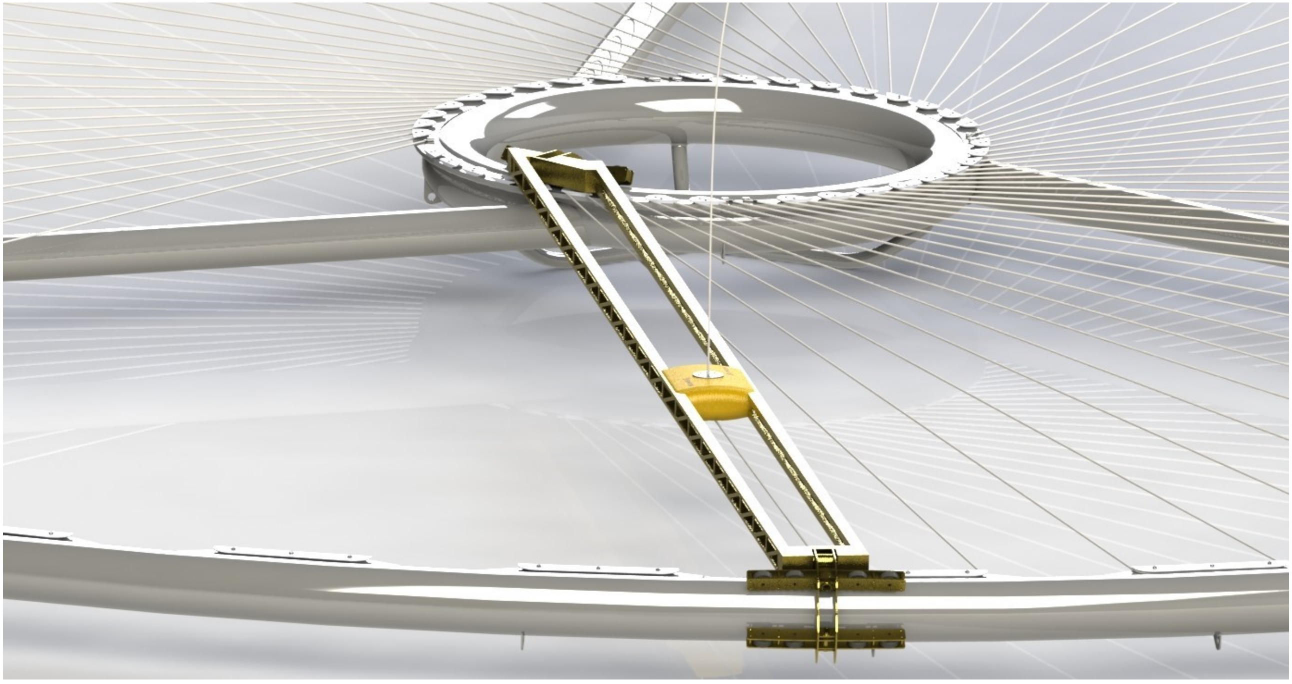
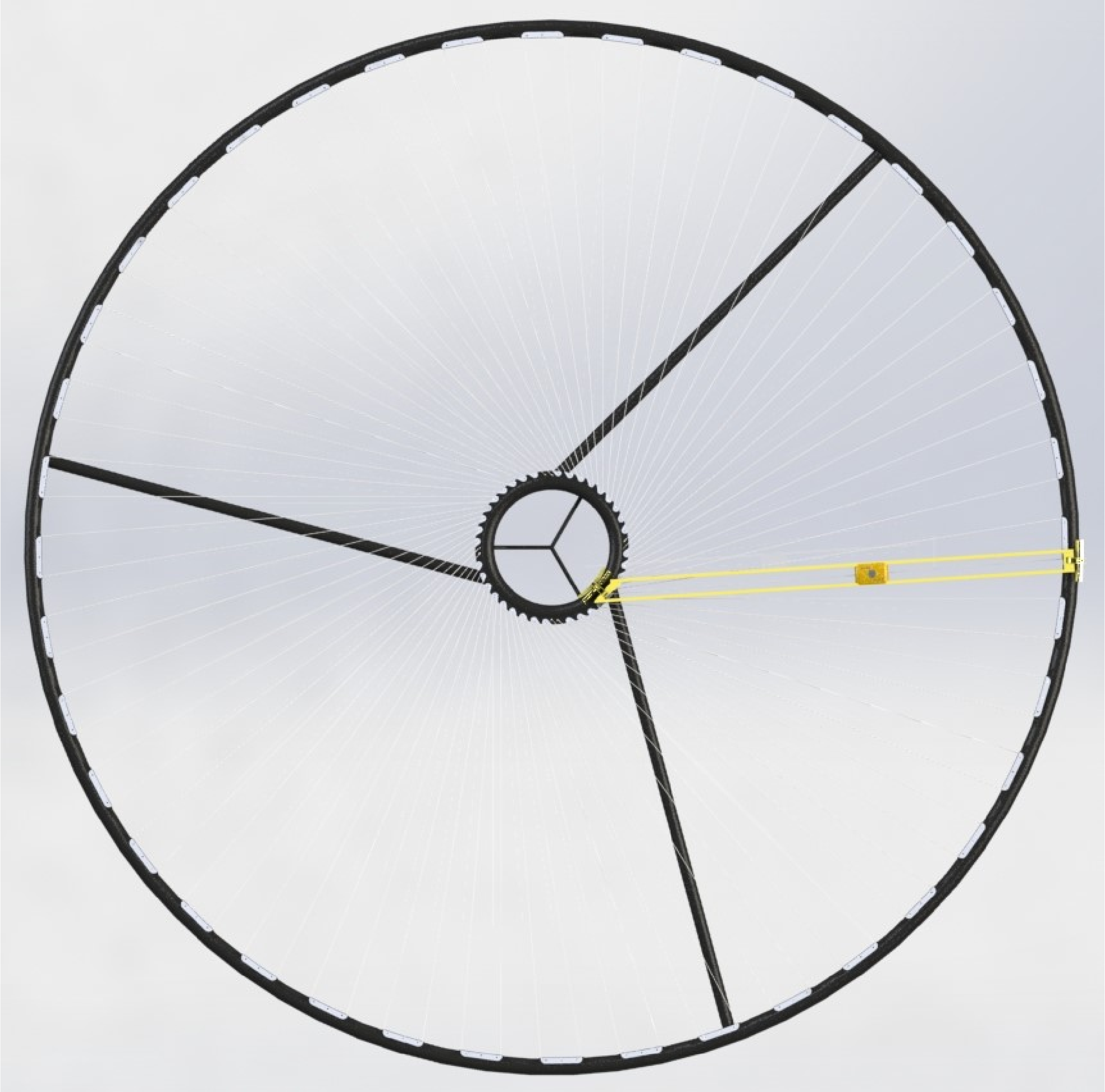
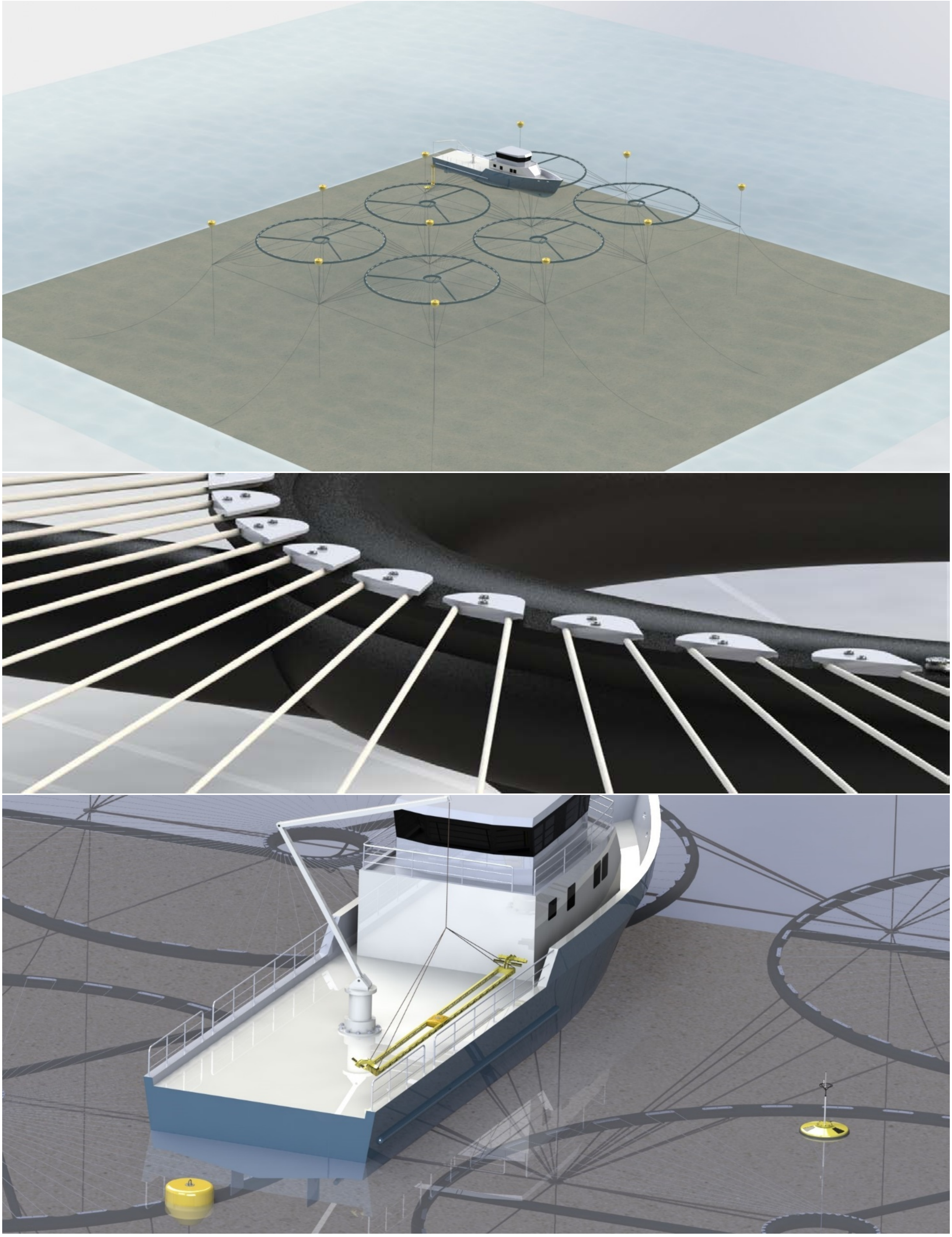
Appendix

A Renders









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