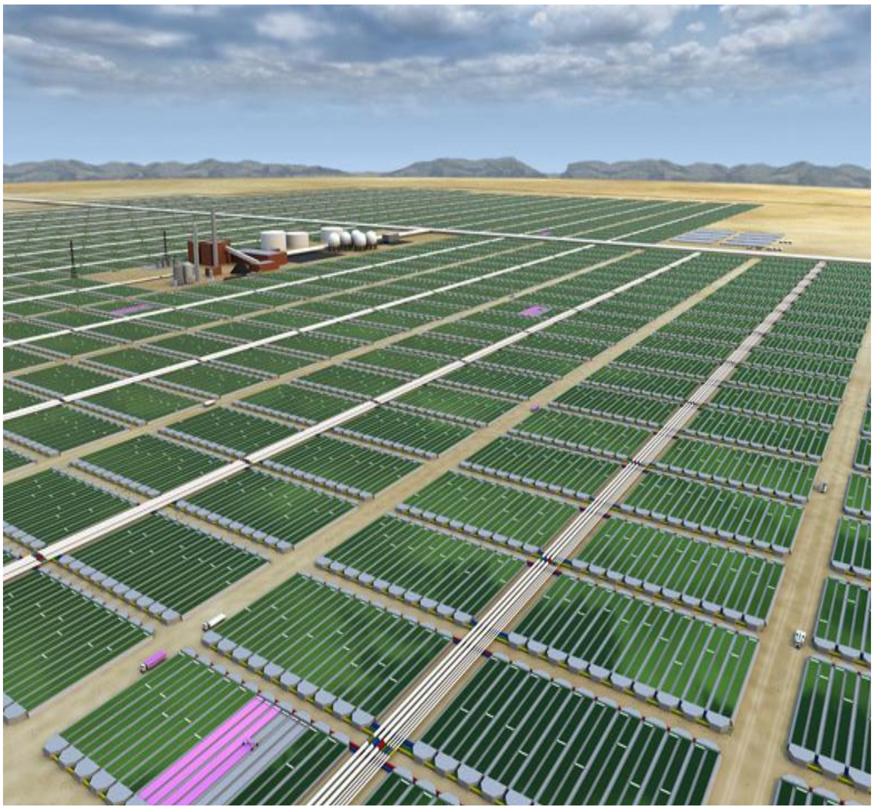
Biomass Refinery and Process Dynamics

Thesis Biomass Refinery and Process Dynamics

Distribution station planning on algae cultivation site



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Abstract

Microalgae are considered one of the most promising feedstock for biofuels and are one of the resources for renewable biodiesel to meet the global demand for transport fuel. Therefore, microalgae for biofuels have to be produced at large scale. In large scale algae cultivation sites, nutrient resources (water, CO_2, nutrients) are supplied from distribution stations. In addition, harvested algae are stored or preprocessed in centralized harvesting or storage units. Distribution of resources and collection of the harvested products through pipelines require energy for pumping. The thesis concerns the development of a simulation tool to evaluate the energy consumption for a large scale algae cultivation site and to study some scenarios for location planning of distribution stations in the algae cultivation site.

The scenario studies illustrate that the length and number of solar collector tubes in the algae cultivation unit have significantly influence on the energy consumption of the algae cultivation units and on the energy consumption of the algae cultivation site. The planned locations of the distribution station affect the place layout of the algae cultivation units and pipeline system planning in the algae cultivation site. The most interesting outcome of the scenario studies is that by using large diameters for the recirculation tubes, algae cultivation units with shorter solar collector tubes need the lowest energy consumption.

Keywords: microalgae, simulation, algae cultivation, distribution

Content

Nomenclature

Variable		***Unit***
Q	Flow capacity	m^3/s
L	Length	m
W	Width (m)	m
E	Energy consumption	W
A	Area	m^2
d	Diameter	m
d_h	Distance between each solar collector tube	m
v_{tube}	Flow velocity of broth	m/s
V	Volume	m^3
N	Number (dimension)	-
F	Multiple-outlet pipe friction head loss factor	-
h_f	Friction head loss (m)	m
h_l	Local head loss(m)	m
K_d	Local head loss factor	-
H	Height	m
Pr	Production	kg
η_e	Efficiency factor of pumps	%
R	Ratio	%
$C_{harvested}$	Concentration of the harvested products in broth	$\mathrm{kg} \cdot m^{-3}$
Subscript		
ctube	Solar collector tube	
stube	Recirculation tube	
gastube	Degassing tube	
sub_pipe	sub pipe in the pipeline system	
main_pipe	Main pipe in the pipeline system	
degass	degasser	
algaeunit	Algae cultivation unit	
algaefield	Algae growth area in the cultivation site	
area	Area of algae cultivation site	
dis	Distribution station	
Transport	Pipeline system	

1. Introduction

Microalgae are considered as one of the most promising feedstock for biofuels and are one of the resources for renewable biodiesel to meet the global demand for transport fuel (Chisti, 2007). Therefore, microalgae for biofuels have to be produced at large scale (Wijffels & Barbosa, 2010). Microalgae production systems have been successfully demonstrated at laboratory and small scale, however, the economical and sustainability of large up-scaling microalgae production still has not been proven(Fridley, 2010; Wijffels & Barbosa, 2010). The major problems of microalgae production up-scaling from small scale to large scale present both economic and technical limits to success(Ferrell & Sarisky-Reed, 2010). The full supply chain of alternative energy from raw materials to manufacturing relied still highly on fossil-fuel energy(Fridley, 2010). Furthermore, the cost of energy for nutrient source supply and harvested production collection are cheap in small scale units, but are significant for large scale production(Ferrell & Sarisky-Reed, 2010).

The layout of large scale algae cultivation site is shown in Figure 1. The production location is composed by many microalgae sub-systems, which also called as algae cultivation units. All these sub unit system are served from a distribution station that is placed in the algae cultivation site. The algae cultivation unit uses water and nutrient resource that distributed from distribution station to yield biomass. Also, the harvested products from the algae cultivation units are transported to the distribution station. The transport of nutrients and harvested products between algae cultivation units and distribution station is undertaken by a pipeline system. However, in the literature it is not yet described where the distribution station in the algae cultivation site should be planned in such large scale algae production site.

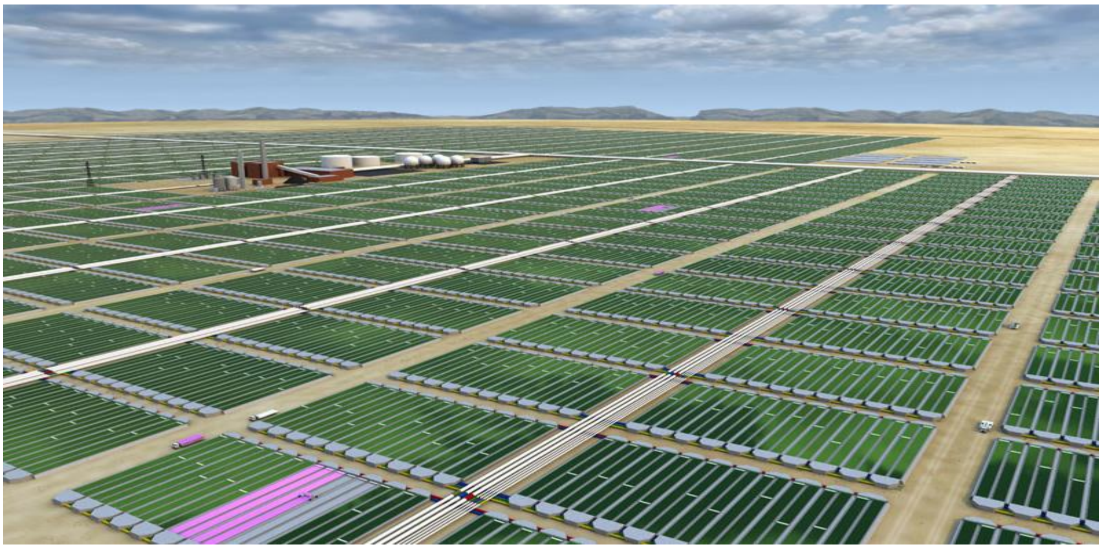

Figure 1 Artists impression for the layout of large scale algae cultivation site.

1.1. Objective of this thesis

The objective of this thesis is to develop and use a simulation tool to evaluate the energy consumption for a large scale cultivation site by changing algae cultivation unit design and location planning of distribution stations in the algae cultivation site.

This study is focused on the energy consumption of resource supply and harvested product collection through the pipeline system and the energy consumption of algae broth in the microalgae cultivation system. The energy consumption of algae growth, the energy consumption of CO_2 injection in the algae cultivation unit and other downstream processing, such as dewatering and flocculation, are not considered in this research.

1.2. Research questions

The planning of the pipeline system is not only affected by the number of algae cultivation units and the design of algae cultivation unit, but also influenced by the locations of distribution station. Therefore, in order to achieve the goal of this study, the following research questions should be answered:

1. What is the energy consumption for nutrient source distribute and harvested products collection of an algae cultivation site?
2. What are the energy consumptions of the algae cultivation site by adapting different dimension designs of the algae cultivation units?
3. What are the effects of different locations of distribution station on the energy consumptions of pipeline system and algae cultivation site?

1.3. Research approach

A mathematical/engineering model was built to calculate the energy consumptions of the algae cultivation unit and the pipeline system. The model is also used to evaluate the effects of different locations of distribution station and pipeline system planning on the energy consumption over large scale algae cultivation site. The structure of the model is described in the Chapter 2.

A large scale algae cultivation site, with production characteristics for a location in the Netherlands which consists of several algae cultivation units, was considered as the research background of this study. The algae cultivation units concern a horizontal tubular photobioreactor system, which is considered as the most promising system for scaling up (Chisti, 2007). The horizontal tubular photobioreactror system consists of solar collector tube, recirculation tube and degasser, the structure of the algae cultivation unit is shown in the Figure 2. The area of large algae cultivation site is $400\text{m} \times 400\text{m}$ and there is one distribution station, which area is $50\text{m} \times 100\text{m}$, in the algae cultivation site. The diameter of pipe in the supply pipeline system is 0.40m. As the sun is available for 12hours per day, the distribution station works 12 hours per day and there are 300 working days a year for algae cultivation site.

The research approach of this study is:

1) Establish the simulation model to calculate the energy consumptions of algae cultivation unit and pipeline system;
2) Using the simulation model to evaluate the effect of different algae cultivation unit designs on the total energy consumption of algae cultivation site;
3) Using the simulation model to evaluate the effect of different distribution station locations on the energy consumptions of algae cultivation site and pipeline system;

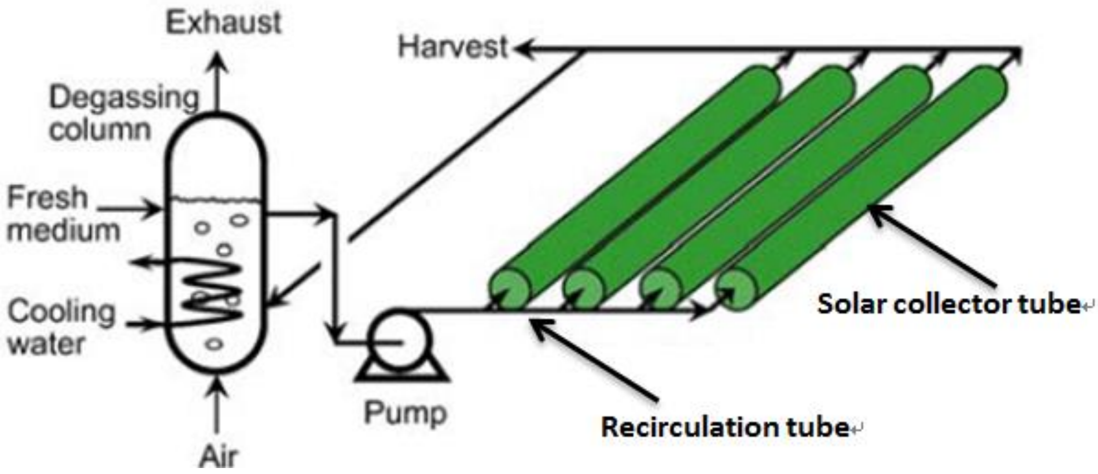

Figure 2 Design of algae cultivation unit (Chisti, 2007)

2. Model-based approach

The research of this study was based on a model-based approach and the structure of the model is shown in Figure 3. The current model consists of two components: the algae cultivation unit model and algae cultivation site model. The inputs of the model are the design details of algae cultivation unit, design details of algae cultivation site, the location and dimension of distribution station. The major outcomes of the model are energy consumption of algae cultivation unit, energy consumption of algae cultivation site, energy consumption of pipeline system and the estimated algae production in the algae cultivation site. The energy and mass balances of the model are described in the following texts.

The model based on following assumptions: 1) the velocity of broth in the tube is constant; 2) the capacity of harvesting flow is equal to the capacity of broth inflow in the algae cultivation unit; 3) the designs and layouts of resource supply pipeline system and harvested products collecting pipeline system are the same; 4) As illustrated by Molina et al., (2001), the liquid velocity of broth has an impact on the maximum allowable length of solar collector tube. However, in this study, the constant liquid velocity is used in the different lengths of solar collector tube.

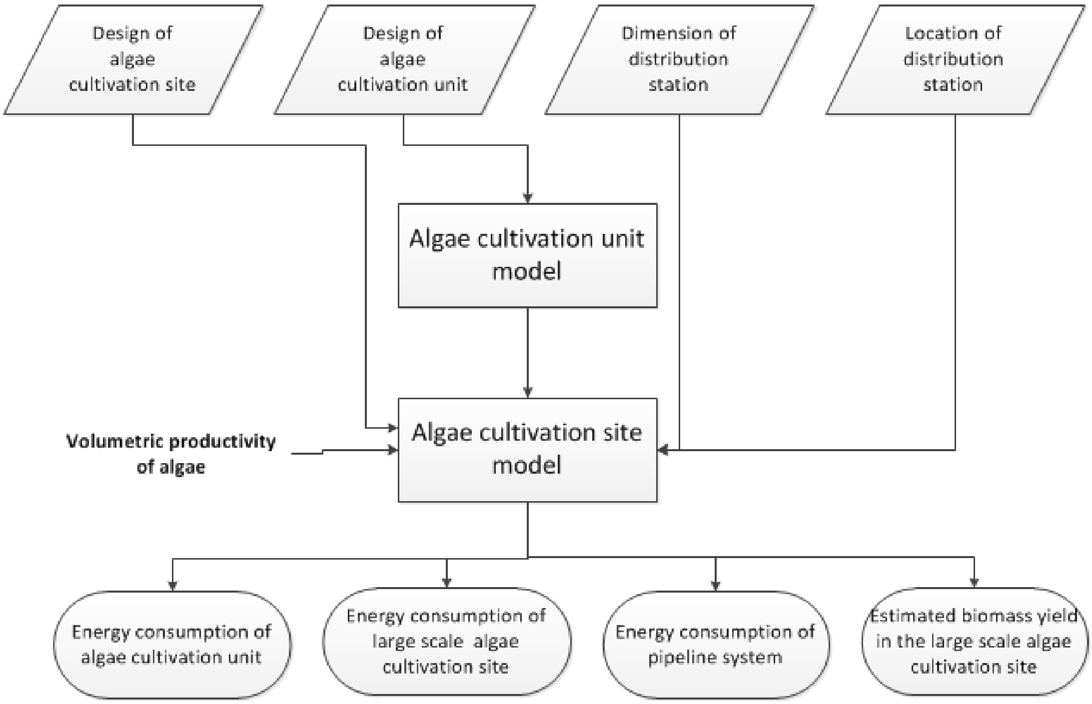

Figure 3 the structure of the model used in this study

2.1. Algae cultivation unit model

The algae cultivation unit model is used to calculate the energy consumption of algae cultivation unit. The structure of the algae cultivation unit used in this study is shown in the Figure 2. The total energy consumption of the algae cultivation unit consists of three parts, which are the energy consumptions of solar collector tube, recirculation tube and the degasser.

2.1.1. Flow capacity of each component in the algae cultivation unit

Flow capacity of solar collector tube Q_{ctube}

$$Q_{ctube} = v_{ctube} \times \pi \times \frac{d_{ctube}^2}{4} \qquad m^3/s \qquad 2.1$$

Where v_{ctube} is the flow velocity of broth in the solar collector tube, m/s; d_{ctube} is the diameter of solar collector tube, m.

Flow capacity of recirculation tube Q_{stube}

Two recirculation tubes are connected with solar collectors in the algae cultivation unit, see Figure 2. The flow capacity of each recirculation tube is the sum of the flow capacity of all solar collector tubes.

$$Q_{stube} = N_{ctube} \times Q_{ctube} \qquad m^3/s \qquad 2.2$$

Where N_{ctube} is the total number of solar collector tubes in the algae cultivation unit.

Flow capacity of degasser $Q_{gastube}$

The degasser is connected with two recirculation tubes in the algae cultivation unit by degassing tube, see Figure 2. Based on the equilibrium of the degasser under the steady state condition, the flow capacity of degasser$Q_{gastube}$ is calculated, see equation 2.3. The oxygen concentration in the broth entering into the degasser, $x_{O_2,in}$, is calculated based on the equation 2.4 (Molina et al., 2001).

$$Q_{gastube} = Q_{stube} \times \frac{x_{O_2,in} - x_{O_2,out}}{x_{air,out} - x_{air,in}} \qquad m^3/s \qquad 2.3$$

$$x_{O_2,in} = R_{O_2} \times \frac{L_{gastube}}{v_{ctube}} + x_{O_2,out} \qquad mol/m^3 \qquad 2.4$$

Where $L_{gastube}$ is the length of degasser tube, which is equal to the length of solar collector tube, m; $x_{O_2,out}$ is the oxygen concentration in the broth leaving the degasser, which is estimated as 0.3mol/m^3; R_{O_2} is the maximum oxygen generation rate, which is equal to 0.003$mol \cdot m^{-3} \cdot s^{-1}$ (Fernández et al., 1998); $x_{air,in}$ is the oxygen concentration of the air flow entering the degasser, which is equal to atmospheric conditions, mol/m^3; $x_{air,out}$ is the oxygen concentration of the air flow leaving the degasser, which estimates equal to twice larger than $x_{air,in}$, mol/m^3.

2.1.2. Energy consumption of each component in the algae cultivation unit

Multiple-outlet pipe friction head loss factor F

The friction head loss in a multiple-outlet pipe is obtained by multiplying the head loss in a fully flowing pipe by a factor *F*, as given below:

$$F = \frac{1}{2.8} + \frac{1}{2 \times N_{outlet}} + \sqrt{\frac{0.8}{6 \times N_{outlet}^2}} \quad - \qquad 2.5$$

Where N_{outlet} is the number of the outlet in the tube. When the N_{outlet} is equal to zero, the *F* is equal to 1(Nir, 1982).

Friction head loss of the tube h_{f_tube}

Due to friction along the length of pipe, the water head of broth would decrease. This water head loss can be calculated by the Darcy-Weisbach equation. In order to better understand the relationship between flow capacity and friction head loss, the Darcy-Weisbach equation with friction factor calculated by Blasius' empirical formula is used to calculate the friction head loss in this study (Nir, 1982), as given below:

$$h_{f\_tube} = 82700 \times \frac{Q_{tube}^{1.75}}{d_{tube}^{4.75}} \times F_{tube} \times L_{tube} \quad m \qquad 2.6$$

Where L_{tube} is the length of tube; $F_{tube}$is multiple-outlet pipe friction head loss factor. In this equation, Q_{tube} is the flow capacity of the tube, m^3/hr; $d_{tube}$is the diameter of the tube, mm.

Local head loss of the tube h_{l_tube}

$$h_{l\_tube} = 6380 \times K_d \times \frac{Q_{tube}^2}{d_{tube}^4} \quad m \qquad 2.7$$

The local head loss equation used in this study is based on the local head loss calculation equation in the hand book of irrigation technology(Nir, 1982). K_d is determined by the state changes of flow, in this case, it is equal to 0.89. In the case of degassing device, h_{l_tube} is equal to the height of degassing device. Q_{tube} is the flow capacity of the tube, m^3/hr; $d_{tube}$is the diameter of the tube, mm.

Energy consumption of solar collector tube E_{ctube}

The friction head loss in the solar collector tube is calculated by the equation 2.6 The local head loss of solar collector tube is equal to zero, due to there is no state changes of flow in the solar collector tube. The energy consumption of solar collector tube is determined by:

$$E_{ctube} = Q_{tube} \times h_{f\_ctube} \times \rho_{water} \times \frac{g}{\eta_e} \quad w \qquad 2.8$$

Where ρ_{water} is the density of water, which is $1000 kg/m^3$; g is the acceleration of gravity, which is $9.81 m/s^2$; $\eta_e$is the pump efficiency.

Energy consumption of recirculation tube E_{stube}

The friction head loss in the recirculation tube is calculated by the equation 2.7. The recirculation tube is perpendicular connected with numbers of solar collector tube in the algae cultivation unit, thus, the local head loss of recirculation tube is calculated by the equation 2.8. The energy consumption of recirculation tube is determined by:

$$E_{stube} = Q_{stube} \times (h_{f\_stube} + h_{l\_stube}) \times \rho_{water} \times \frac{g}{\eta_e} \qquad w \qquad 2.9$$

ρ_{water} is the density of water, which is 1000kg/m^3; g is the acceleration of gravity, which is 9.81m/s^2; $\eta_e$is the pump efficiency.

Energy consumption of degasser E_{degass}

The friction head loss in the degasser tube is calculated by the equation 2.7. The local head loss of degasser tube is equal to height of degasser. The energy consumption of degasser is determined by:

$$E_{degass} = Q_{gastube} \times (h_{f\_gastube} + H_{degass}) \times \rho_{water} \times \frac{g}{\eta_e} \qquad w \qquad 2.10$$

ρ_{water} is the density of water, which is 1000kg/m^3; g is the acceleration of gravity, which is 9.81m/s^2; $\eta_e$is the pump efficiency; H_{degass} is the mounting height of degasser, m.

Total energy consumption of algae cultivation unit $E_{algaeunit}$

The total energy consumption of algae cultivation unit consists of energy consumption of solar collector tubes, energy consumption of recirculation tubes and energy consumption of degasser.

$$E_{algaeunit} = (E_{ctube} \times N_{ctube} + 2 \times E_{stube} + E_{degass})/1000 \qquad kw \qquad 2.11$$

2.1.3. The dimension of algae cultivation unit

The lengths of degassing tube $L_{gastube}$ and recirculation tube L_{stube}

$$L_{gastube} = L_{ctube} \qquad m \qquad 2.12$$

$$L_{stube} = d_{ctube} \times N_{ctube} + d_h \times (N_{ctube} - 1) \qquad m \qquad 2.13$$

Where L_{ctube} is the length of solar collector tube, m; d_{ctube} is the diameter of solar collector tube, m; d_h is the distance between each solar collector tube, m.

2.2. Algae cultivation site model

The algae cultivation site model was used to predict the total algae production in the algae cultivation site and calculate the energy consumption of algae cultivation site. Total energy consumption of the algae cultivation site includes the total energy consumption of algae cultivation units in the algae cultivation site and the energy consumption of pipeline system for transporting nutrient resource and harvesting biomass. For the layout of pipeline system, there are two major types of pipe using in the pipeline system, the sub pipe and main pipe. The diameters of sub pipe and main pipe are the same. The sub pipe is connected with each algae cultivation unit, see Figure 5, the nutrients and harvested biomass from algae cultivation unit are directly transported and collected by the sub pipe. The main pipe is serviced as the collector and transporter between the sub pipes and distribution station. The main pipe is parallel to the solar collector tube. The distribution station locates in the middle of working area of algae cultivation site, see Figure 5. The rest space of the working area is designed for roads and other downstream processing equipment.

Three pipeline system layouts for the situation that the distribution station locates in the different locations of the algae cultivation site are available in the model, see Figure 4. The different locations of distribution station in the algae cultivation site include the distribution station locates in the east side of algae cultivation site, see Figure 4 (a), the distribution station locates in the north side of algae cultivation site, see Figure 4 (b) and the distribution station locates in the north side of algae cultivation site, see Figure 4 (c).

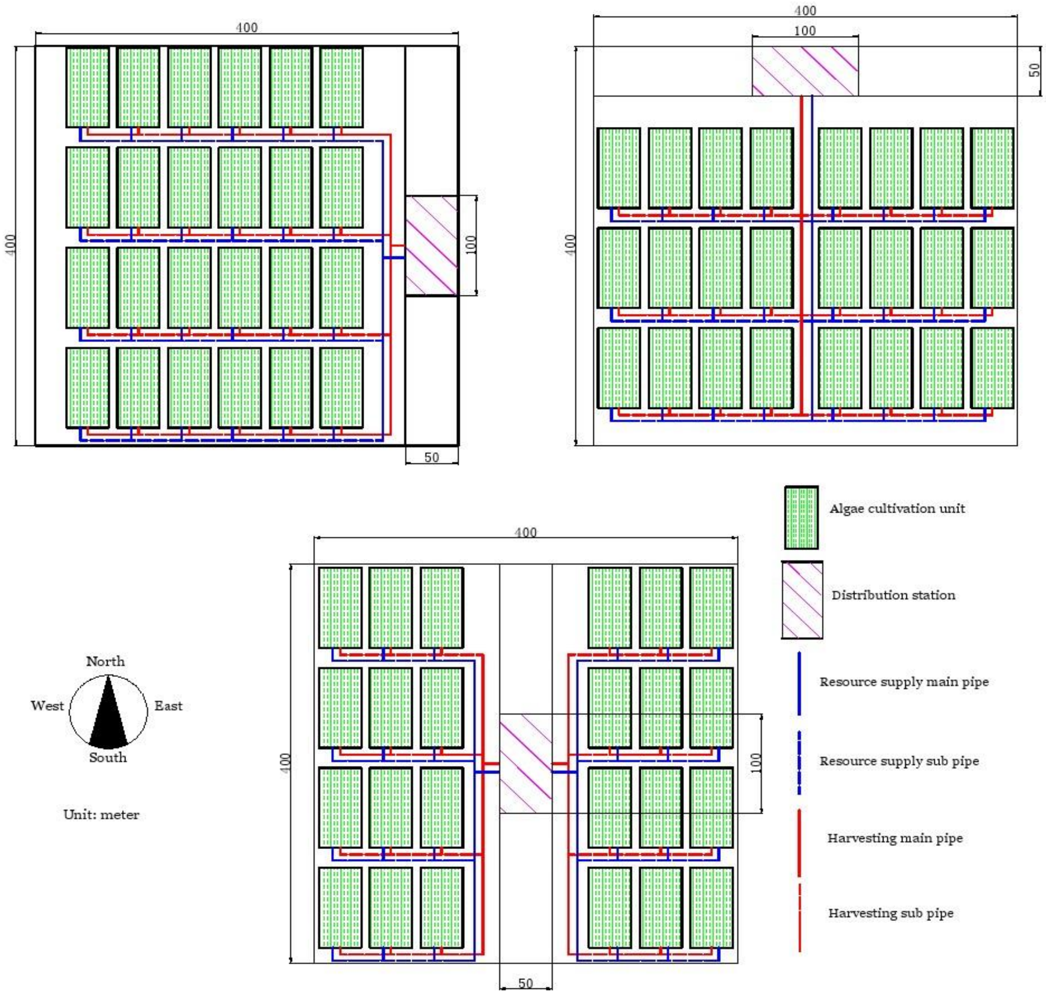

Figure 4 Pipeline system planning and distribution station layouts for three different locations in the algae cultivation site. The distribution station located in the east side of algae cultivation site is shown in the Figure 4(a); The distribution station located in the north side of algae cultivation site is shown in the Figure 4(b);the distribution station located in the middle of algae cultivation site is shown in the Figure 4(c).

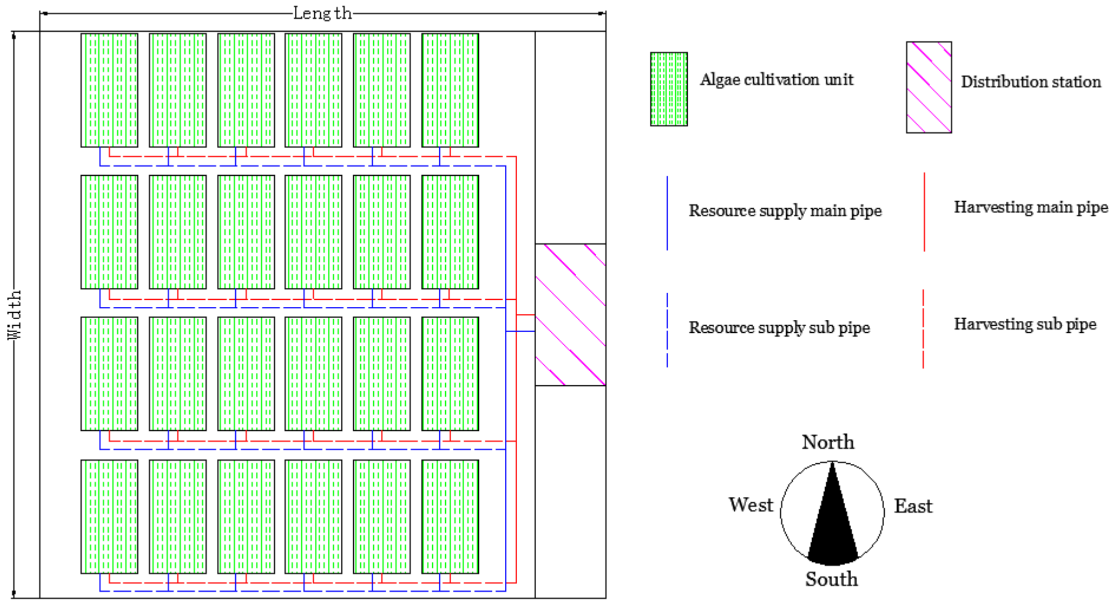

Figure 5 the pipeline system planning and algae cultivation unit layouts in the algae cultivation site

2.2.1. Dimensions of algae cultivation unit and the algae growth area in the algae cultivation site

Area of algae cultivation unit $A_{algaeunit}$

Taking the space for extra pipeline, pumps and other equipment in the algae cultivation unit into account, the length and width of the algae cultivation unit needs to increase 10%, respectively.

$$A_{algaeunit} = L_{stube} \times L_{ctube} \times 1.1 \times 1.1 \quad m^2 \quad 2.14$$

Where L_{stube} is the length of recirculation tube, m; L_{ctube} is the length of solar collector tube, m.

Area of the algae growth area $A_{algaefield}$

When the distribution station is located in the east side or middle of algae cultivation site, see Figure 4 (a) and (c), the area of algae growth area in the algae cultivation site is given as:

$$A_{algaefield} = L_{area} \times W_{area} - W_{area} \times W_{dis} \quad m^2 \quad 2.15$$

When the distribution station is located in the north side of algae cultivation site, see Figure 4 (b), the area of algae growth area in the algae cultivation site is given as:

$$A_{algaefield} = L_{area} \times W_{area} - L_{area} \times W_{dis} \quad \mathrm{m}^2 \quad 2.16$$

2.2.2. Dimension and layout design of pipeline system

The number of algae cultivation units in the algae cultivation site $N_{algaeunit\_total}$

The number of algae cultivation units is depended on the number of algae cultivation units along the length side ($N_{algaeunit\_length}$) and the number of algae cultivation units along the width side ($N_{algaeunit\_width}$), see Figure 5.

When the distribution station is located in the east side or middle of algae cultivation site, see Figure 4 (a) and (c), the total number of algae cultivation units in the algae cultivation site is:

$$N_{algaeunit\_length} = \frac{L_{area} - W_{dis}}{L_{stube} \times 1.1} \quad 2.17$$

$$N_{algaeunit\_width} = \frac{W_{area}}{L_{ctube} \times 1.1} \quad 2.18$$

$$N_{algaeplot\_total} = N_{algaeplot\_length} \times N_{algaeplot\_width} \quad 2.19$$

Where L_{area} is the length of the algae cultivation site, m; W_{area} is the width of the algae cultivation site, m; W_{dis} is the width of the distribution station, m.

When the distribution station is located in the north side of algae cultivation site, see Figure 4, the total number of algae cultivation units in the algae cultivation site is:

$$N_{algaeunit\_length} = \frac{L_{area}}{L_{stube} \times 1.1} \quad 2.20$$

$$N_{algaeunit\_width} = \frac{W_{area} - W_{dis}}{L_{ctube} \times 1.1} \quad 2.21$$

$$N_{algaeunit\_total} = N_{algaeunit\_length} \times N_{algaeunit\_width} \quad 2.22$$

2.2.3. Flow of each component in the pipeline system

Flow capacity of single sub pipe in the pipeline system Q_{sub_pipe}

The flows of nutrients supply and harvested products collection are assumed the same in this study. Under steady state conditions the equilibrium of the nutrient supply flow in the algae cultivation unit is given as:

$$Q_{supply} \times C_{harvested} = Pr_{algae} \times V_{ctube} \times \frac{N_{ctube}}{12hr \times 3600s/hr} \quad m^3/s \quad 2.23$$

Where Q_{supply} is the flow capacity of the sub pipe supply to the algae cultivation unit, m^3/s; Pr_{algae} is the biomass volumetric productivity, $\mathrm{kg \cdot m^{-3} \cdot day^{-1}}$; $C_{harvested}$ is the concentration of harvested products in the broth, kg/m^3, the value of $C_{harvested}$ is estimated to be the same as Pr_{algae}; V_{ctube} is the volume of single solar collector tube, $\mathrm{m^3}$. Note: the term $\frac{1}{12hr \times 3600s/hr}$ is used to transform the unit of Pr_{algae} from $\mathrm{kg} \cdot m^{-3} \cdot day^{-1}$ to $\mathrm{kg} \cdot m^{-3} \cdot s^{-1}$

The single sub pipe is connected with number of algae cultivation units along the length side of algae cultivation site, see Figure 5. Therefore, the flow capacity of single sub pipe is:

$$Q_{sub\_pipe} = N_{algaeunit\_length} \times Q_{supply} \qquad m^3/s \qquad 2.24$$

Where $N_{algaeunit\_length}$ is the number of algae cultivation units along the length side of algae cultivation site.

Flow capacity of single main pipe in the pipeline system Q_{main_pipe}

The main pipe is connected with number of sub pipes in the algae cultivation site, see Figure 5. The flow capacity of main pipe depends on the number of sub pipes in the algae cultivation site.

$$Q_{main\_pipe} = N_{sub\_pipe} \times Q_{sub\_pipe} \qquad m^3/s \qquad 2.25$$

Where N_{sub_pipe} is the number of sub pipes in the algae cultivation site and it depends on the $N_{algaeunit\_width}$ and the pipeline planning of pipeline system, see Figure 4.

2.2.4. Energy consumption of pipeline system in the algae cultivation site

Energy consumption of the sub pipe E_{sub_pipe}

$$E_{sub\_pipe} = Q_{sub\_pipe} \times (h_{f\_sub\_pipe} + h_{l\_sub\_pipe}) \times \rho_{water} \times \frac{g}{1000} \qquad kw \qquad 2.26$$

Where $h_{f\_sub\_pipe}$ and $h_{l\_sub\_pipe}$ are the friction head loss and local head loss in the single sub pipe, which are calculated by the equation 2.6 and equation 2.7.

Energy consumption of the main pipe E_{main_pipe}

$$E_{main\_pipe} = Q_{main\_pipe} \times (h_{f\_main\_pipe} + h_{l\_main\_pipe}) \times \rho_{water} \times \frac{g}{1000} \qquad kw \qquad 2.27$$

Where $h_{f\_main\_pipe}$ and $h_{l\_main\_pipe}$ are the local head loss and friction head loss in the single main pipe, which are calculated by the equation 2.6 and equation 2.7.

Energy consumption of pipeline system $E_{transport}$

The energy consumption of the pipeline system consists of total energy consumption of sub pipes and total energy consumption of main pipes.

$$E_{transport} = (N_{sub\_pipe} \times E_{sub\_pipe} + N_{main\_pipe} \times E_{main\_pipe}) \qquad kw \qquad 2.28$$

$$E_{transport\_total} = 2 \times E_{transport} \qquad kw \qquad 2.29$$

In this study, the designs and layouts of resource supply pipeline system and biomass product harvesting pipeline system are assumed to be the same. Therefore, the energy consumption of pipeline transport system, $E_{transport\_total}$, in the cultivation site is twice larger than that of resource supply pipeline system. N_{main_pipe} is the number of sub pipes in the algae cultivation site and it depends on the pipeline planning in the pipeline system, see Figure 4. N_{sub_pipe} is the number of sub pipes in the algae cultivation site and it depends on the $N_{algaeplot\_width}$ and the pipeline planning of pipeline system, see Figure 4.

Under the situation of distribution station locates in the east side of algae cultivation site:

$$N_{sub\_pipe} = N_{algaeunit\_width} \quad 2.30$$

Under the situation of distribution station locates in the north side or middle of algae cultivation site:

$$N_{sub\_pipe} = 2 \times N_{algaeunit\_width} \quad 2.31$$

Total energy consumption of algae cultivation site $E_{algaefield}$

The total energy consumption of algae cultivation site includes total energy consumption of algae cultivation units and the total energy consumption of pipeline systems.

$$E_{algaefield} = E_{algaeunit} \times N_{algaepunit\_total} + E_{transport\_total} \qquad kw \quad 2.32$$

Estimate biomass production in the algae cultivation unit and the algae cultivation site

$$Pr_{algaeunit} = Pr_{algae} \times V_{ctube} \times N_{ctube} \qquad \mathrm{kg} \cdot \mathrm{day}^{-1} \quad 2.33$$

$$Pr_{algaefield} = Pr_{algaeunit} \times N_{algaeunit\_total} \times \frac{300\ day}{1000} \qquad \mathrm{ton} \quad 2.34$$

Where $Pr_{algaeunit}$ and $Pr_{algaefield}$ are the estimated biomass yield of algae cultivation unit and algae cultivation site, respectively. Pr_{algae} is the biomass volumetric productivity that based on Molina (2001), 2.5 $\mathrm{kg} \cdot m^{-3} \cdot \mathrm{day}^{-1}$; V_{ctube} is the volume of single solar collector tube, m^3; N_{ctube} is the total number of solar collector tube in the algae cultivation unit. $N_{algaeunit\_total}$ is the total number of algae cultivation unit in the algae cultivation site.

2.2.5. Land usage ratio

The land usage ratio depends on the total area of algae cultivation units and the algae growth area in the algae cultivation site:

$$R_{land} = \frac{A_{algaeunit} \times N_{algaeunit\_total}}{A_{algaefield}} \times 100\% \qquad \% \quad 2.35$$

Where R_{land} is the land usage ratio of algae cultivation units;

3. Methodology

There were three different location layouts of distribution station in the algae cultivation site studying in the following scenario studies, which were the distribution station located in the north side of algae cultivation site, the distribution station located in the east side of algae cultivation site and the distribution station located in the middle of algae cultivation site. The layouts of pipeline system planning of those different locations of distribution station are shown in the Figure 4. The diameters of sub pipe and main pipe in the pipeline system are 0.4m. The design details of algae cultivation unit used in the following scenario studies are described in Table 1. The simulation time for following scenario studies was one year.

Table 1 the design detail of unit algae cultivation unit

Algae cultivation unit design l	Unit	Value	Reference
Diameter of solar collector tube	m	0.06	(Molina et al., 2001)
Diameter of recirculation tube	m	0.40	Estimate
Horizontal distance between each solar collector tube	m	0.05	(Slegers et al., 2013)
Daily areal biomass production	kg m^{-3} day^{-1}	2.5	(Molina et al., 2001)
Tube material	-	Glass	(Slegers et al., 2013)
The linear broth velocity	m/s	0.5	(Molina et al., 2001)
Length of the solar collector tube	m	40, 80,160	Estimate
The number of solar collector tube	-	200, 100, 50	Estimate
Pump efficiency	%	70	Estimate

The performance indicators for the following scenario studies were:

In order to compare the energy consumption of the algae cultivation sites that are installed with different designs of algae cultivation unit under the same land usage ratio, the performance indictor R_{E_Pr} was used. The equation for calculating R_{E_Pr} is shown below. It represents that the energy consumption of algae cultivation site to produce 1kg algae production when the algae growth area of algae cultivation site is 100% covered by the algae cultivation units.

$$R_{E\_Pr} = \frac{E_{algaefield} \times 12hr \times 300day}{Pr_{algaefield} \times 1000 \times R_{land}} \qquad \text{kwh/kg} \qquad 3.1$$

Where $E_{algaefield}$ is the total energy consumption in the algae cultivation site, kw; $Pr_{algaefield}$ is the total biomass production in the algae cultivation site, ton; R_{land} is the land usage ratio of algae cultivation site.

3.1. The effects of algae cultivation unit design on the energy consumption of algae cultivation site

In order to address the first and second research questions, different designs of algae cultivation unit were simulated in the algae cultivation site. In this scenario study, different algae cultivation unit designs were placed in the algae cultivation site that the distribution station was located in the east-side of algae cultivation site. The planned layout of the pipeline system is presented in Figure 4(a). In order to focus on the energy consumption issue and to evaluate the effect of different designs of the algae cultivation unit on pipeline planning and the total energy requirement of algae cultivation site, therefore, the biomass yield of algae cultivation unit needs to be the same.

According to the equation 2.33, the biomass yield of algae cultivation unit is depended on the volume and the number of solar collector tube in the algae cultivation unit. As the diameter of solar collector tube is a constant value that shows in Table 1. Thus, the biomass yield of algae cultivation unit is depended upon the length and the number of solar collector tube in the algae cultivation unit.

For that reason, the total length of solar collector tubes in the algae cultivation unit should be the same, which equals here to 8000m. There are three different designs of algae cultivation unit that used in the scenario study and the design details of those algae cultivation units are shown in Table 2.

Table 2 Design information of different designs of algae cultivation unit

Design of algae cultivation unit	Length of solar collector tube	Number of solar collector tubes
Design I algae unit	40m	200
Design II algae unit	80m	100
Design III algae unit	160m	50

3.2. The effects of different locations of distribution station on the energy consumption of the algae cultivation site

In order to answer the third research question, the different locations of distribution station in the algae cultivation site were simulated. The chosen design of the algae cultivation unit is the design II algae unit, the design detail of it is described in Table 1 and Table 2. There are three simulated algae cultivation site, the algae cultivation site with a distribution station located in the north side (north location), the algae cultivation site with a distribution station located in the east side (east location) and the algae cultivation site with a distribution station located in the middle (middle location). The layouts of pipeline system and distribution station in the algae cultivation site for those three location case are shown in Figure 4.

4. Results

4.1. The effects of algae cultivation unit design on the energy consumption of algae cultivation site

4.1.1. The energy consumption of algae cultivation unit

The energy consumption of algae cultivation unit consist of three parts, the total energy consumption of solar collector tubes, the energy consumption of recirculation tubes and the energy consumption of degassing tube. In Table 3, the energy consumption of design I algae unit is the highest among other designs of algae cultivation unit.

Table 3 the total energy consumptions of different algae cultivation unit designs

Design of algae cultivation unit	$E_{algaeunit}$ (w)
Design I algae unit	3934
Design II algae unit	2211
Design III algae unit	2691

The total energy consumption of solar collector tubes

It can be seen in Table 4, the energy consumption of single solar collector tube is increased as the length of solar collector tube increases. Total energy consumptions of solar collector tubes for each design of algae cultivation unit were the same. The reason for that is that the total energy consumption of solar collector tubes, based on Eq. 2.6, 2.8 and 2.11, were dependent on the multiplying result of solar collector tube length and the number of solar collector tubes in the algae cultivation unit, as the flow capacity of solar collector tube in each design of algae cultivation unit was the same. Table 2 shows that the multiplying result of solar collector tube length and the number of solar collector tubes in different designs of algae cultivation unit are the same.

Table 4 the energy consumptions of solar collector tube for different algae cultivation unit designs

Design of algae cultivation unit	E_{tube} (w)	N_{tube}	E_{tube_all} (w)
Design I algae unit	4	200	800
Design II algae unit	8	100	800
Design III algae unit	16	50	800

The total energy consumption of recirculation tube

As we can see in Table 5, the energy consumption of recirculation tube in the design I algae unit is the highest. It was 9 times higher than the energy consumption of recirculation tube in the design II algae unit and 74 times higher than the energy consumption of recirculation tube in the design III algae unit.

The major cause for that was the different total amount of the flow capacity of recirculation tube in the each algae cultivation unit, see Table 5. According to the Eq. 2.1, the flow capacity of solar collector tube was the same in the each design of algae cultivation unit. However, as the total number of solar collector tubes in each design of algae cultivation unit were not the same. Therefore, based on the Eq. 2.2, the flow capacity of the recirculation tube in each design of algae cultivation unit were not the same. Furthermore, as indicated by the equation 2.13, the length of the recirculation tube also depends on the number of solar collector tubes in the algae cultivation site. Because of the design I algae unit has the largest number of solar collector tubes, see Table 2, the energy consumption of recirculation tube in the design I algae unit was the largest.

Table 5 the liquid flows, the lengths and the energy consumptions of recirculation tube

Design of algae cultivation unit	Q_{stube} (m^3/s)	L_{stube} (m)	E_{stube} (w)
Design I algae unit	0.28	22.0	1179
Design II algae unit	0.14	11.0	137
Design III algae unit	0.07	5.5	16

The energy consumption of degassing device

Table 6 shows that, the oxygen concentration in the inlet of the degasser for the design I algae unit is the lowest. The reason for that is, based on Eq. 2.4 and Table 2, the length of solar collector tube in the design I algae unit is the lowest when compared with other algae cultivation unit designs. The flow capacity of the degasser for all designs of algae cultivation unit is the same, as shows in Table 6.

Table 6 Liquid inflow of degasser and the oxygen concentration in the liquid entering the degasser

Design of algae cultivation unit	$x_{in,O2}$ (mol/m^3)	Q_{degas} (L/s)
Design I algae unit	0.54	72
Design II algae unit	0.78	72
Design III algae unit	1.26	72

In Table 7, the degasser in the design III algae unit has the largest energy consumption. Based on the Eq. 2.6 and 2.10, as the flow capacity of degasser was the same in each algae cultivation unit design, the energy consumption of degasser was increased as the length of degas tube increased.

Table 7 Energy consumption of degassing device for different algae cultivation unit designs

Design of algae cultivation unit	E_{degas} (w)
Design I algae unit	767
Design II algae unit	1128
Design III algae unit	1850

4.1.2. The energy consumption of the supply pipeline system in the east location case

As we can see from Table 8, after placing the different designs of algae cultivation units in the algae cultivation site, the numbers of algae cultivation units along the length side and width side of the algae cultivation site were different. The algae cultivation site could place more design I algae units than the other designs of algae cultivation unit. In addition, the algae cultivation site could place the same number of the algae cultivation units for design II algae unit and design III algae unit.

Table 8 Layouts of different algae cultivation unit designs in the algae cultivation site

Design of algae cultivation unit	$N_{algaeunit\_length}$	$N_{algaeunit\_width}$	$N_{algaeunit\_total}$
Design I algae unit	14	9	126
Design II algae unit	29	4	116
Design III algae unit	58	2	116

The layout of the algae cultivation unit in the algae cultivation site, based on the equations from 2.24 to 2.31, would have an influence on the layout and energy consumption of pipeline system. The energy consumption of single sub pipe was increased as the total number of algae cultivation units along the length side of algae cultivation site was increased. The algae cultivation site that placed with design I algae units has 9 sub pipes and it was around twice larger the number of sub tubes in the algae cultivation site that placed with design II algae units and about 4 times larger the number of sub pipes in the algae cultivation site that placed with design III algae units.

The energy consumption of supply pipeline system in the algae cultivation site that placed with design III algae units was the highest, see Table 9 and Figure 6. The reason for that is the algae cultivation site that placed with design III algae unit has the largest flow capacity of the sub pipe and the length of sub pipe for each design of algae cultivation unit was almost the same, see Table 10. Therefore, based on the equation 2.26, the energy consumption of sub pipe in the algae cultivation site that placed with design III algae units is the highest.

Table 9 Energy consumption of the pipeline system

Design of algae cultivation unit	N_{sub_pipe}	E_{sub_pipe} (kw)	E_{main_pipe} (kw)	$E_{transport}$ (w)
Design I algae unit	9	0.02	1.4	1.6
Design II algae unit	4	0.08	1.2	1.6
Design III algae unit	2	0.28	1.6	2.1

Table 10 Lengths and liquid flows of sub pipe and main pipe in the pipeline system

Design of algae cultivation unit	L_{sub_pipe} (m)	Q_{sub_pipe} (L/s)	L_{main_pipe} (m)	Q_{main_pipe} (L/s)
Design I algae unit	338	7	396	66
Design II algae unit	349	15	352	61
Design III algae unit	348	30	352	61

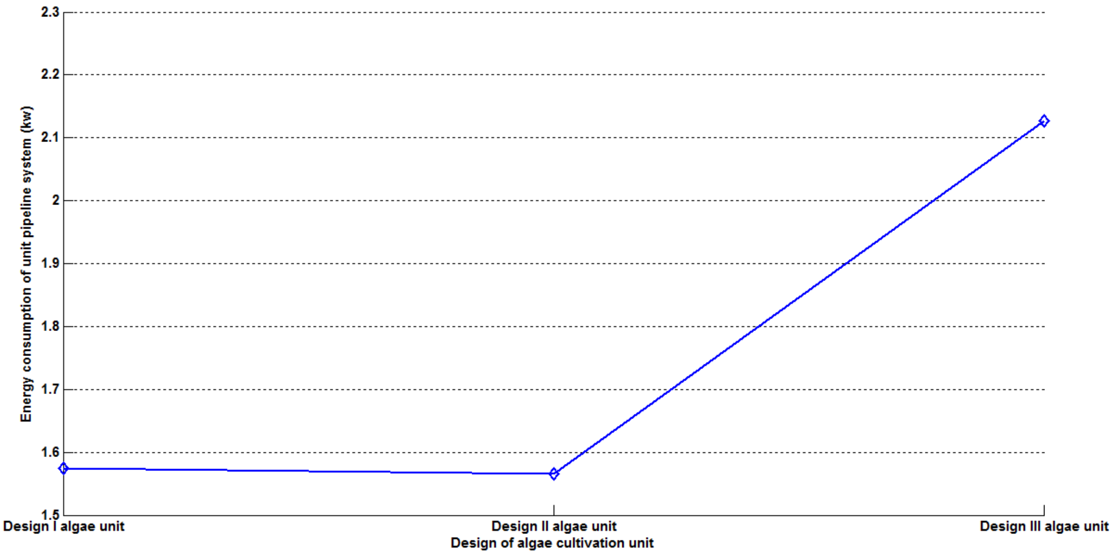

Figure 6 Energy consumption of unit pipeline system of the algae cultivation sites with different designs of algae cultivation unit

4.1.3. The energy requirement and production of the algae cultivation site

Figure 7 shows that the algae cultivation site placed with design I algae units consumed higher amount energy than the algae cultivation site placed with other designs of algae cultivation units. Although the algae cultivation site could be placed with the same number of design II algae units and design III algae units, the energy consumption of design III algae unit was higher than that of design II algae unit. Therefore, the total energy consumption of algae cultivation site that placed with design III algae units was higher than the total energy consumption of algae cultivation site placed with design II algae units.

In view of algae production of algae cultivation site, the algae production of the algae cultivation site that placed with design I algae units was the highest, and the algae productions of the algae cultivation site placed with other designs of algae cultivation unit were nearly the same. The reason for that is the total biomass production of the algae cultivation site, see Eq. 2.33 and 2.34, is determined by the biomass production of single algae cultivation unit and the total number of algae cultivation units placed in the cultivation site. As the biomass production of each algae cultivation unit was the same, the total biomass production of algae cultivation site was increased as the total number of algae cultivation units in the algae cultivation site, see Table 8, increased.

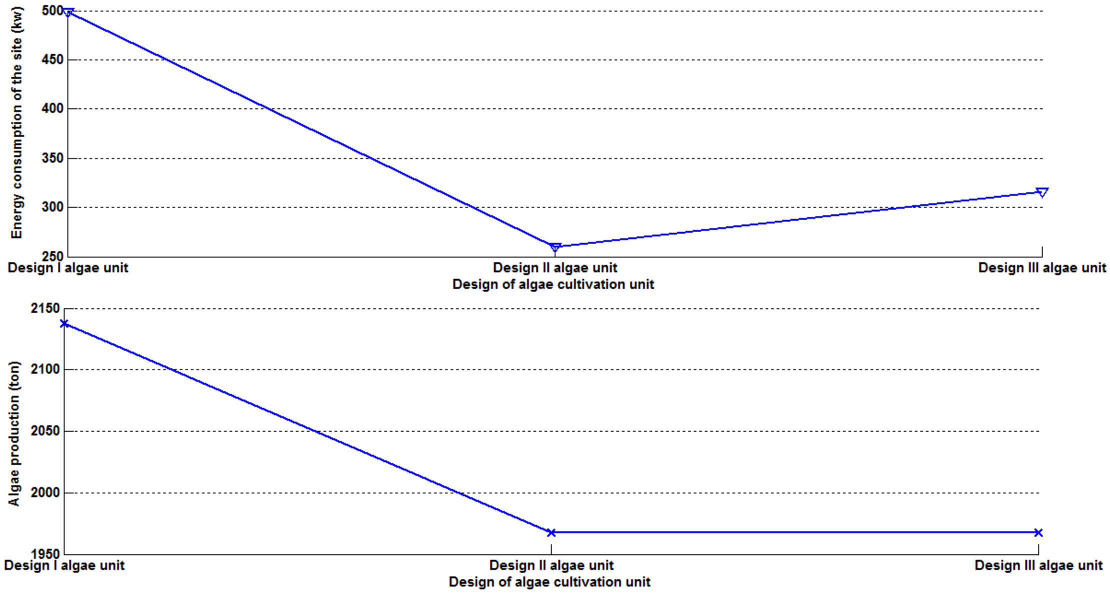

Figure 7 the energy consumption and biomass production of algae cultivation site that placed with different designs of algae cultivation unit

Furthermore, according to the Table 11, the land usage ratios of the algae cultivation site are different. The algae cultivation site placed with the design I algae units had the highest land usage ratio.

Table 11 Land usage ratio of algae cultivation sites that applied with different designs of algae cultivation unit

Design of algae cultivation unit	Land usage ratio
Design I algae unit	96%
Design II algae unit	88%
Design III algae unit	87%

According to the Figure 8, the R_{E_Pr} of the algae cultivation site placed with design II algae units was the lowest, which was 0.54kwh/kg. That means the algae cultivation site required 0.54kwh to produce 1 kg biomass production when the algae growth area was fully covered by the design II algae units.

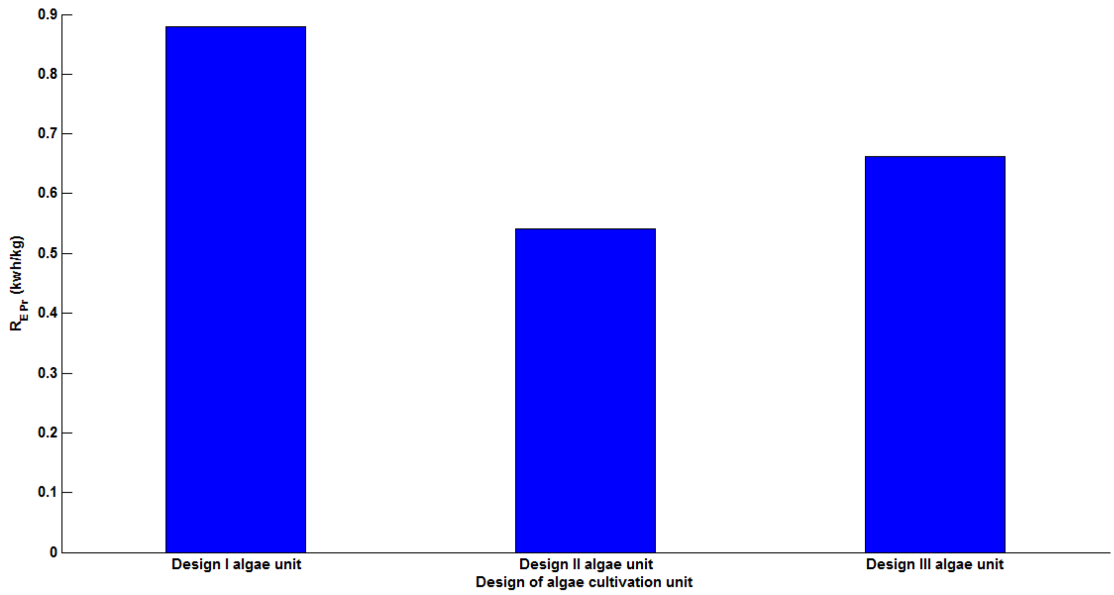

Figure 8 the R_{E_Pr} of algae cultivation sites that applied with different designs of algae cultivation unit

4.2. The effects of different locations of distribution station on the energy requirement of the algae cultivation site

The total energy consumption of algae cultivation site and energy consumption of pipeline system was the lowest in the north location case, see Table 12. As can be seen in Table 13, the major reason for that is the total number of the algae cultivation units in the north location case was the smallest.

Table 12 Energy consumption of algae cultivation site and pipeline system for the situation that the distribution station located in the different location in the algae cultivation site

Location of distribution station	$E_{algaefield}$ (kw)	$E_{transport}$ (kw)	Production (ton)
East location	260	1.57	1968
North location	220	0.78	1680
Middle location	258	0.83	1968

In Table 12 and 13, in both east location and middle location cases, the total number of algae cultivation units in the algae cultivation site was the same. However, the energy consumption of pipeline system of the east location case was around twice higher than that of the middle case. The reason for that the different pipeline planning, see Figure 4, affected the energy consumptions of each sub pipe and main pipe. Compared with the pipeline planning in the east location case, the middle location case had a shorter length of sub pipe and lower number of algae cultivation units in the single tube. Therefore, the energy consumption of single sub pipe in the middle location case was much smaller than the energy consumption of single sub pipe in the east location case, see Table 14. Both east location case and north location case had the same total flow capacity of the pipeline system. However, there were two main pipes in the middle location case and the flow capacity in the single main pipe was half of that in the east location case. That was result in a significantly reduction on the energy consumption of the single main pipe.

Table 13 Layout of algae cultivation unit in the algae cultivation site

Design of algae cultivation unit	$N_{algaeunit\_length}$	$N_{algaeunit\_width}$	$N_{algaeunit\_total}$
East location	29	4	116
North location	33	3	99
Middle location	29	4	116

Table 14 the layout and energy consumption of sub pipe and main pipe in the algae cultivation site for different distribution station location cases

Location of distribution station	N_{sub_pipe}	E_{sub_pipe} (w)	N_{main_pipe}	E_{main_pipe} (w)
East location	4	82	1	1237
North location	6	19	1	668
Middle location	8	14	2	361

As in the north location case, the number of the algae cultivation units could be placed in the algae cultivation site is the lowest, as can be seen in the Table 13, the land usage ratio of the north location case was the smallest, as presents in Table 15.

Table 15 land usage ratio of algae cultivation site

Location of distribution station	Land usage ratio
East location	88%
North location	75%
Middle location	88%

According to the $\mathrm{R_{E\_Pr}}$ of each location case, see Figure 9, the east location case had the highest $\mathrm{R_{E\_Pr}}$ value when compared with other location case. The $\mathrm{R_{E\_Pr}}$ values of other location cases were similar. Therefore, when the distribution station located in the east side of algae cultivation site, the algae cultivation site required to consume more energy to produce 1kg biomass than other location cases. As can be seen in Table 12, although the total consumption of algae cultivation site for the middle location case was higher than that of north location case, the $\mathrm{R_{E\_Pr}}$ for those two location case were almost the same, see Figure 9.

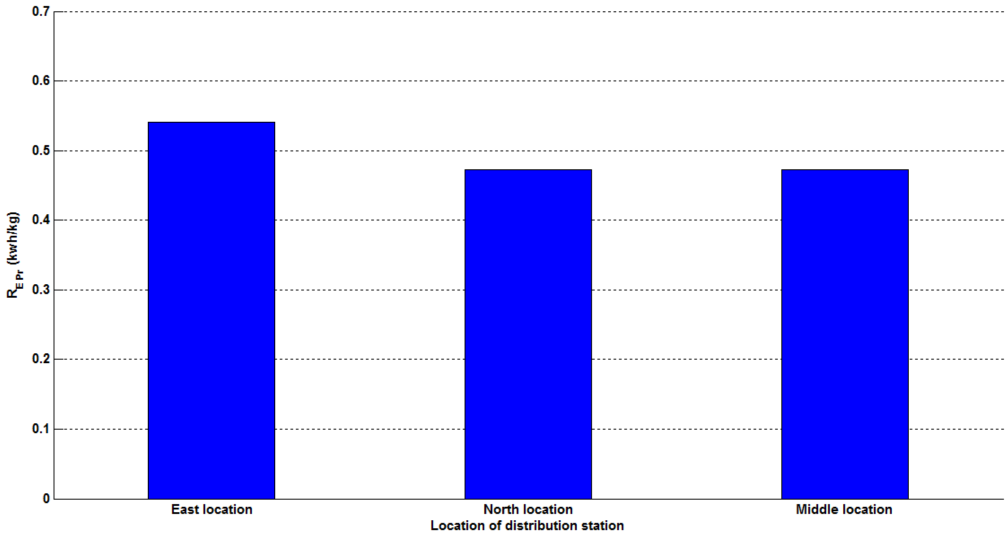

Figure 9 the R_{E_Pr} of different locations of distribution station in the algae cultivation sites

5. Discussion

5.1. Diameter of recirculation tube

For the results in the section 4.1, the energy consumption of single design I algae unit is higher than other algae cultivation unit designs, as show in Table 3. The major cause for that is the large difference in the energy consumption of recirculation tube, as can be seen in Table 5. The recirculation tube energy consumption of design I algae unit is 9 times and 74 times larger than the recirculation tube energy consumptions of design II algae unit and design III algae unit, respectively. Based on the Eq. 2.6, 2.7 and 2.9, when the diameter of tube is a constant, the energy consumption of the recirculation tube is determined by flow capacity and length of the recirculation tube. It can be seen in Table 5, for design I algae unit, the flow capacity and length of the recirculation tube is the largest. However, when increased the current diameter of recirculation tube, 0.4m, the energy consumption of recirculation tube in the design I algae cultivation unit decreased. For that reason, the diameter of recirculation tube range from 0.4m to 1m was simulated. The simulation results are shown in Table 16.

Table 16 the simulation results of energy consumption of recirculation tube and degassing device in the design I algae unit

Diameter of recirculation tube (m)	E_{stube} (w)	$E_{algaeunit}$ (w)	Decrement of energy consumption of algae cultivation unit (w)
0.40	1179	3934	-
0.45	725	3026	908
0.50	470	2515	511
0.55	318	2211	305
0.60	222	2020	191
0.65	160	1896	124
0.70	118	1812	84
0.75	89	1754	58
0.80	68	1713	41
0.85	53	1683	30
0.90	42	1660	22
0.95	34	1644	16
1.00	28	1631	13

Both the energy consumption of the recirculation tube and the energy consumption of the design I algae unit were decreased as the recirculation tube diameter increased. Moreover, the decrement of energy consumption of algae cultivation unit also decreased as the diameter of recirculation tube increased. As can be seen in Table 16 and Figure 10, the decrement for the energy consumption of algae cultivation unit is large in the range from

0.40m to 0.65m. After that the decrement of energy consumption of algae cultivation unit is small and the energy consumption of algae cultivation unit tend to close 1600w.

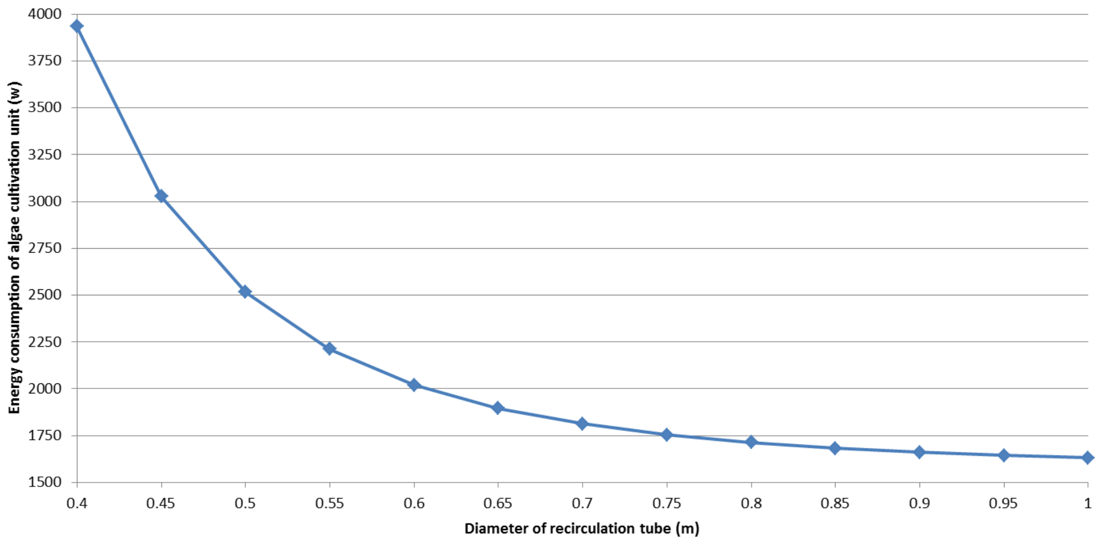

Figure 10 the energy consumptions of design I algae unit for different recirculation tube diameter

Furthermore, when simulated the design II algae unit and design III algae unit in the same diameter range of recirculation tube, the results are shown in Figure 11 and 12. The decrement of the energy consumption of those two designs of algae cultivation unit is not that large as the design I algae unit.

It can be seen in Figure 10, 11 and 12, the decrement of energy consumptions of all three designs of algae cultivation unit tended to be stable after the diameter of recirculation tube is 0.7m. Moreover, when the diameter of recirculation tube is larger than 0.7m, the order of the energy consumption of algae cultivation unit from high to low is design III algae unit, design II algae unit and design I algae unit, although design I algae unit has the largest flow capacity in the recirculation tube. The reason for that is the energy consumption of degasser would take up a large part of the energy consumption of algae cultivation unit and the energy consumption of degasser for design III algae unit is the highest, as can be seen in Table 7.

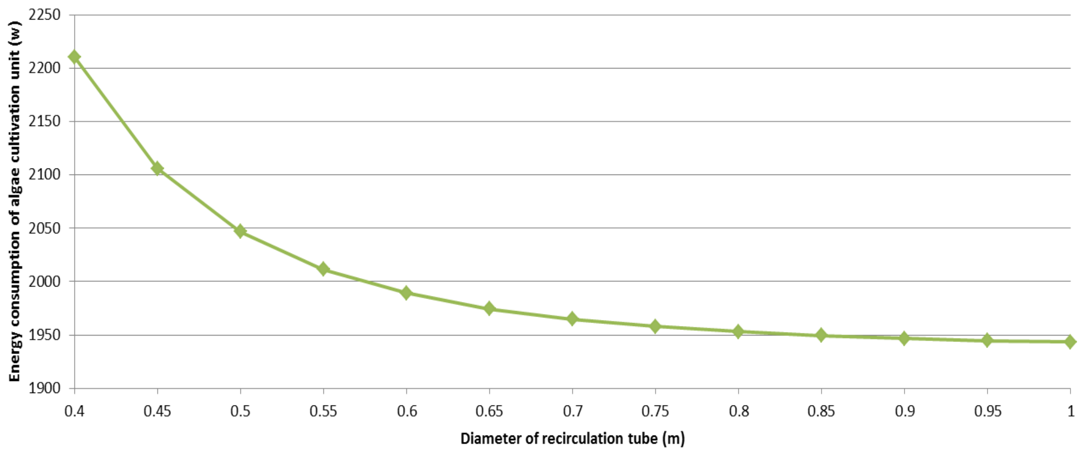

Figure 11 the energy consumptions of design II algae unit for different recirculation tube diameter

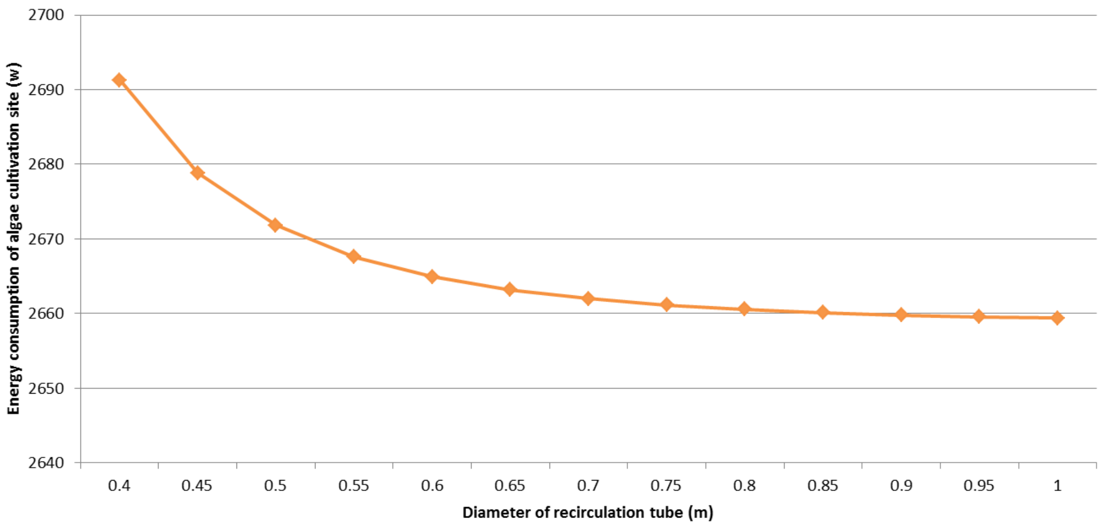

Figure 12 the energy consumptions of design III algae unit for different recirculation tube diameter

When used 0.7m as the diameter of recirculation tube, re-simulated the three algae cultivation unit designs under the same scenario conditions as section 3.1, the R_{E_Pr} of all deigns of algae cultivation unit were smaller than the R_{E_Pr} in the scenario that used 0.4m as the diameter of recirculation tube. Furthermore, the R_{E_Pr} of design I algae unit was much smaller than the R_{E_Pr} in the scenario that used 0.4m as the diameter of recirculation tube.

Based on the R_{E_Pr} results of using 0.7m as the diameter of recirculation tube, see Figure 13, the design I algae unit had the lowest R_{E_Pr} value, and the R_{E_Pr} increased as the length of solar collector tube increased.

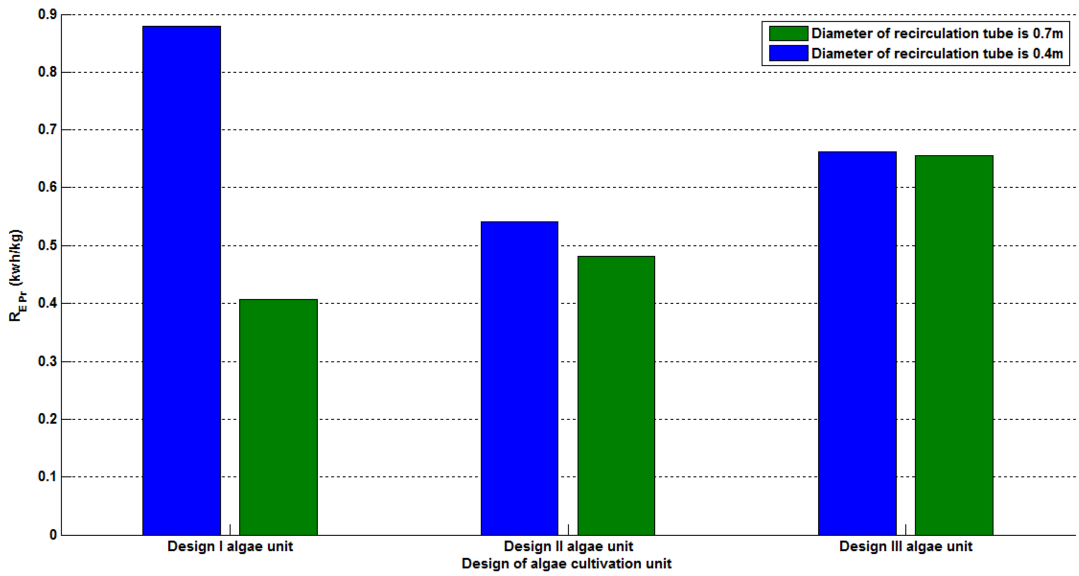

Figure 13 R_{E_Pr} of different diameter of recirculation tube used in the algae cultivation unit designs

5.2. Effect of degassing device on the energy consumption of algae cultivation site

The length of solar collector tube is limited due to the oxygen accumulation in the tube (Molina et al., 2001). The shorter length of solar collector tube accumulates less amount of oxygen. According to the results of section 4.1, in design I algae unit, the oxygen concentration of broth entering the degasser is 0.54mol • m^{-3}, see Table 6. The different between the oxygen concentration of broth entering the degasser and the oxygen concentration of broth leaving the degasser is 0.24mol • m^{-3}. This difference is much smaller than the difference in the algae II cultivation unit and the difference in algae III cultivation unit, which are 0.48 mol • m^{-3} and 0.96 mol • m^{-3}, respectively. Assumed the algae photosynthesis in the design I algae unit may not be inhibited by moving out the degassing device. The design I algae unit was simulated under the conditions of section 3.1 except for not using degasser and change the diameter of recirculation tube to 0.7m. According to the new scenario results, the energy consumption of design I algae unit decreases from 1812w to 1045w and the R_{E_Pr} reduced to 0.24kwh/kg. It is much lower when compared with previous value, 0.41kwh/kg.

6. Conclusions

The simulation model has been built to evaluate effects of different algae cultivation unit designs and different planning of distribution stations on the energy consumption of algae cultivation site. Based on the simulation results of this study, the energy consumption for water distribution and collection of cultivated algae for harvest is much lower in comparison to the total energy consumption of algae cultivation units in an algae cultivation site.

For different algae cultivation unit designs which produce the same amount of biomass, the energy consumption of algae cultivation unit is affected by the length of solar collector tube and the number of the solar collector tubes in the algae cultivation units.

The layout and energy consumption of the supply pipeline system are also affected by the number and length of the solar collector tubes in the cultivation units. Using different designs of the algae cultivation unit in the algae cultivation site results in different flow velocities in the supply pipeline. Supply pipe lines with the lowest flow capacity have the lowest energy consumption for nutrients supply and harvest product collection.

When the diameter of recirculation tube in the cultivation units is large enough, then the energy consumption of the algae cultivation unit depends mainly on the energy consumption of solar collector tubes and the degasser. Then a short length of solar collector tube requires the lowest amount of energy.

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