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# The sustainability assessment of a conceptual multi-purpose offshore platform in South China Sea

## 南シナ海における多目的浮体システムの持続可能性評価

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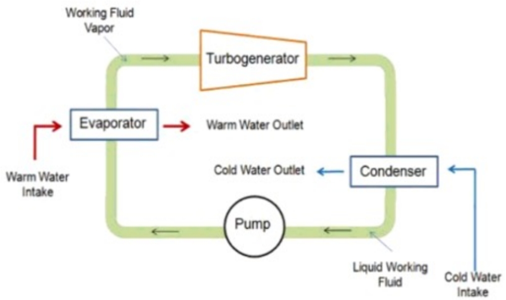
# Introduction

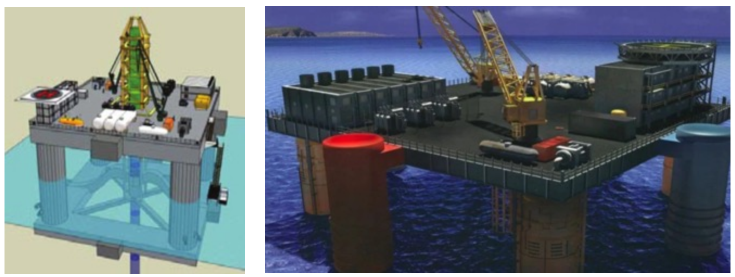
# 1 Introduction: Research background

## Ocean Thermal Energy Conversion (OTEC)




Schematics of OTEC systems (Harrison, 2010)

## OTEC situated on offshore floating platforms



OTEC plant situated on a semi-sub platform (Lockheed, 2014)

## Multi-purpose offshore platforms

**TROPOS**
(EU-FP7 project, 2012-2015)

*Integrated a range of functions from the transport, energy (OTEC), aquaculture and leisure sectors.*

**The Blue Growth Farm**
(EC project, 2018-2021)

*Automated aquaculture and renewable energy production systems are integrated for profitable applications.*

# 1 Introduction: Research background

**When OTEC is integrated with other offshore technologies on a multi-purpose platform…**

**Merits**

- Less dependence on the energy transmission from land to platform
- The combination with other technologies may enlarge the benefit of OTEC
- Reduce the environmental impacts through synergies among single impact
- Successful demonstration cases in Europe

**Problems**

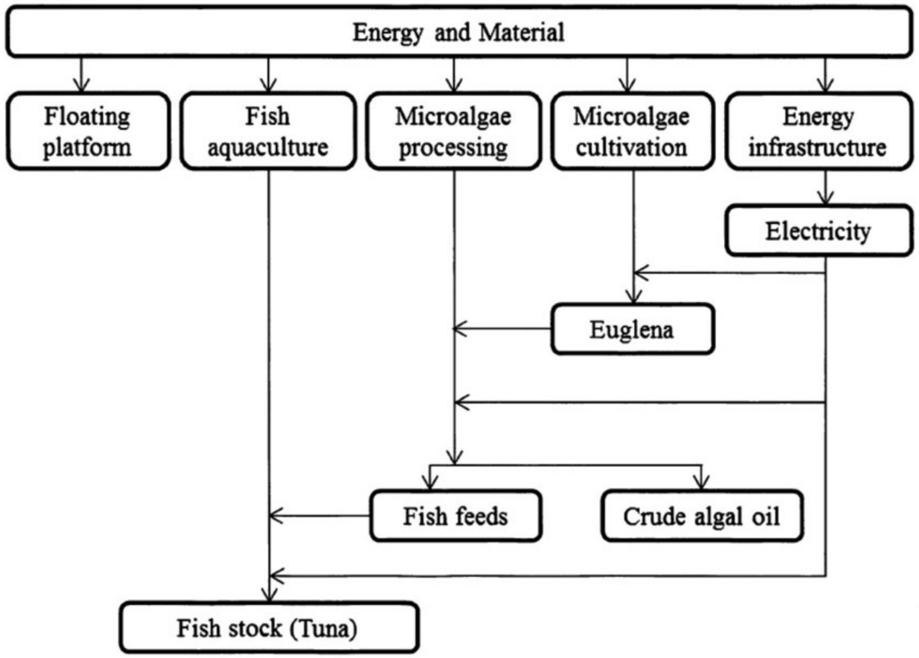
- Uncertain economic feasibility
- The accumulated effects of large scale structures on the marine environment
- Few commercial cases and researches offering references

**An integrated sustainability assessment is necessary.**

# 1 Introduction: Multi-purpose system design

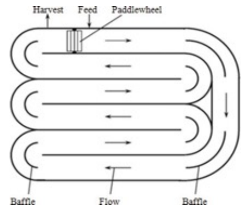
**A cooperative research** with Dr. Duan (the Canon Institute for Global Studies)

- **Previous Study: Conceptual Multi-purpose Offshore Platform (Duan, 2019)**



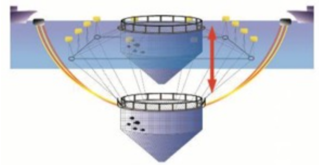

**System Boundary**

- **Microalgae Cultivation System**



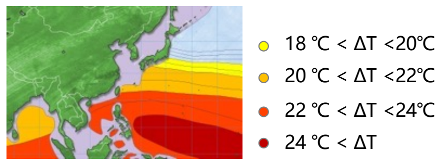

Open raceway pond for microalgae cultivation

- **Tuna Aquaculture System**



The floating/sinking fish culturing system

- **Independent Energy Supply: OTEC**




OTEC Energy Resource in South China Sea

# 1 Introduction: Objectives

The objectives of this research are to ensure the scenario ecologically valuable and feasible when OTEC is combined with other technologies, and provide suggestions to future multi-purpose platform development.

- **Site Selection**

  Ensure the feasibility of siting this conceptual platform in South China Sea.

- **Inclusive Index Evaluation**

  Use inclusive index to evaluate the economical and environmental sustainability to construct this platform.

- **Environmental Impact Simulation**

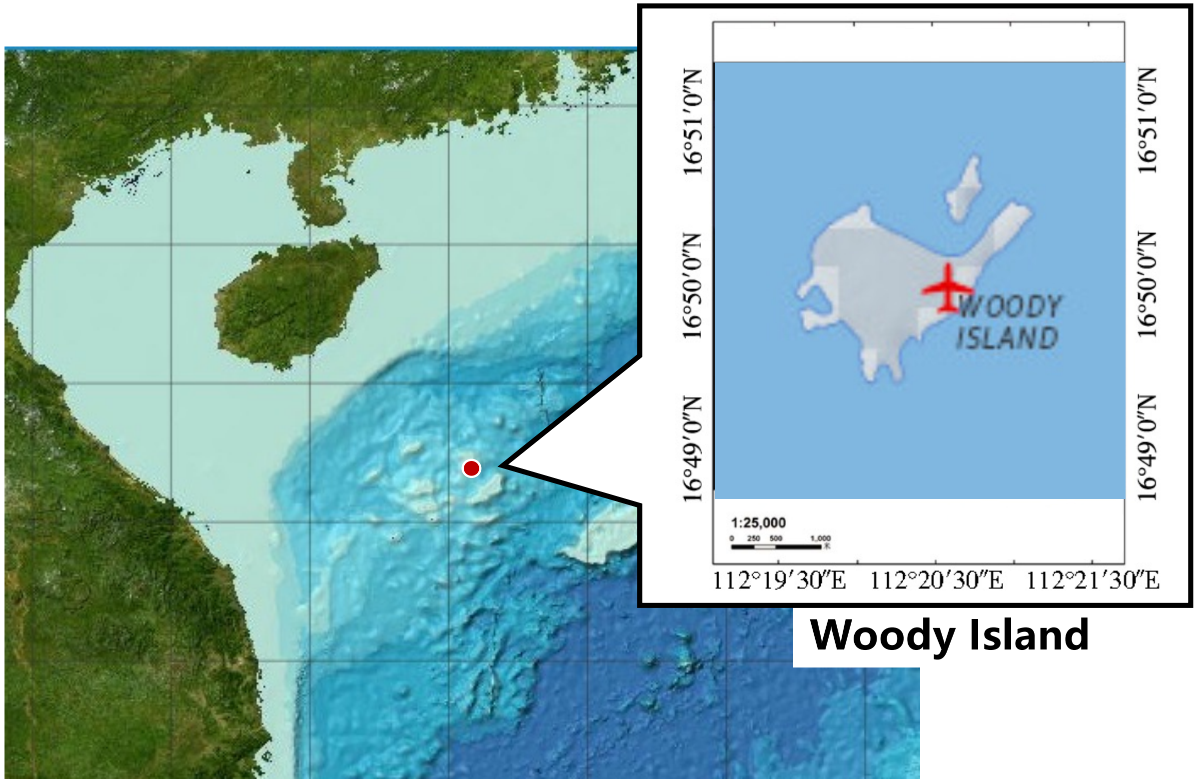
  Use numerical models to simulate the environmental impacts of the platform, focusing on the influences of discharged water and the large-scale floating structure on water qualities and planktons.

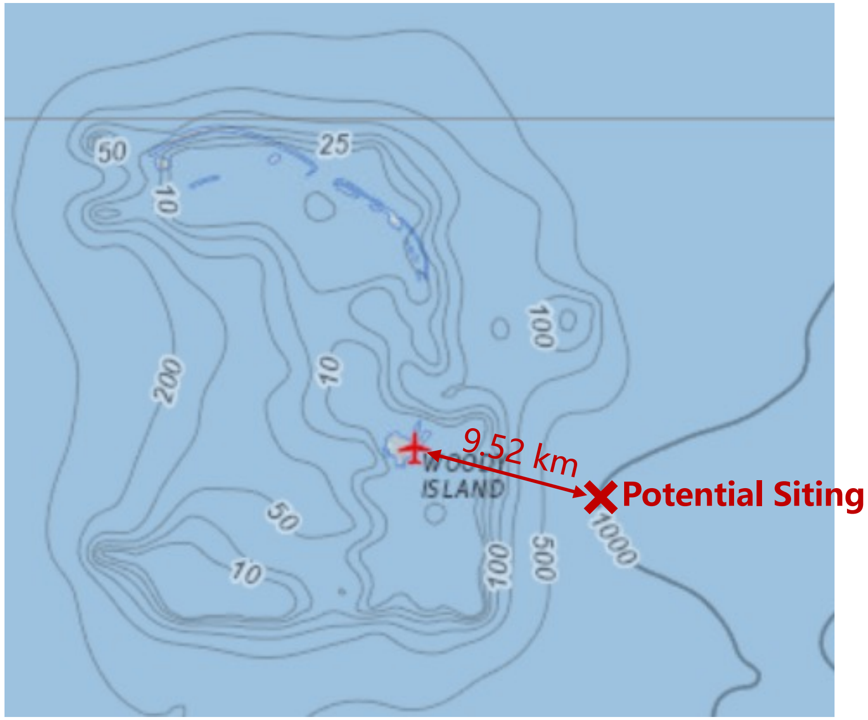
2

# Site Selection

# Site Selection: Woody Island in the South China Sea

- **Potential site of the multi-purpose offshore platform**



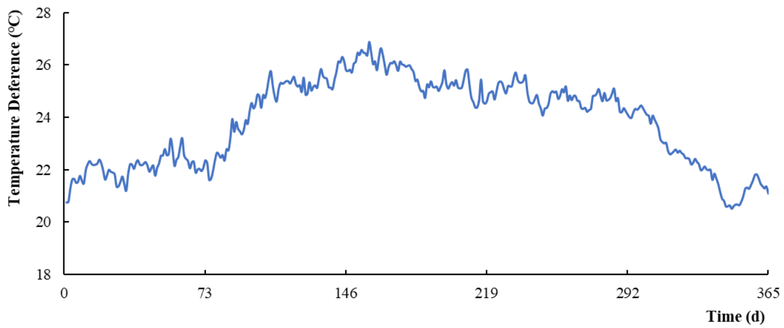

*Bathymetric near Woody Island*

*(NOAA, 2019)*

# 2 Site Selection: Woody Island in the South China Sea

## Abundant ocean thermal energy resource

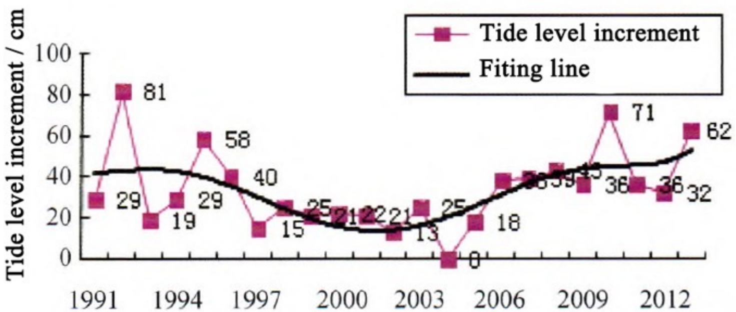
- **Average temperature difference:** 23.85 ℃




The water temperature difference near Woody Island (20190101-20191231)

## Stable climatic conditions

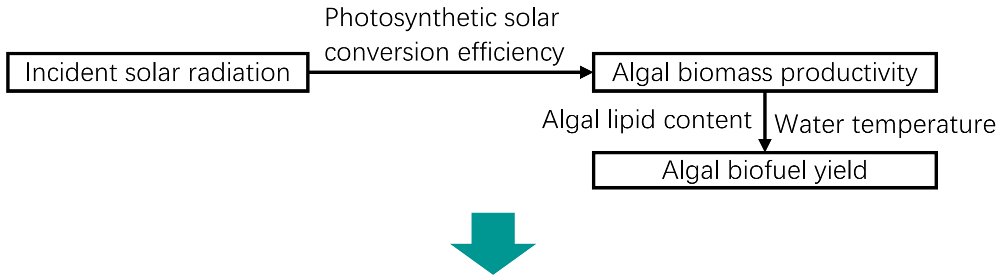
**Annual highest tide level increment**: 34cm
**Only 2 times** when the **typhoon surge warning** reached **blue**

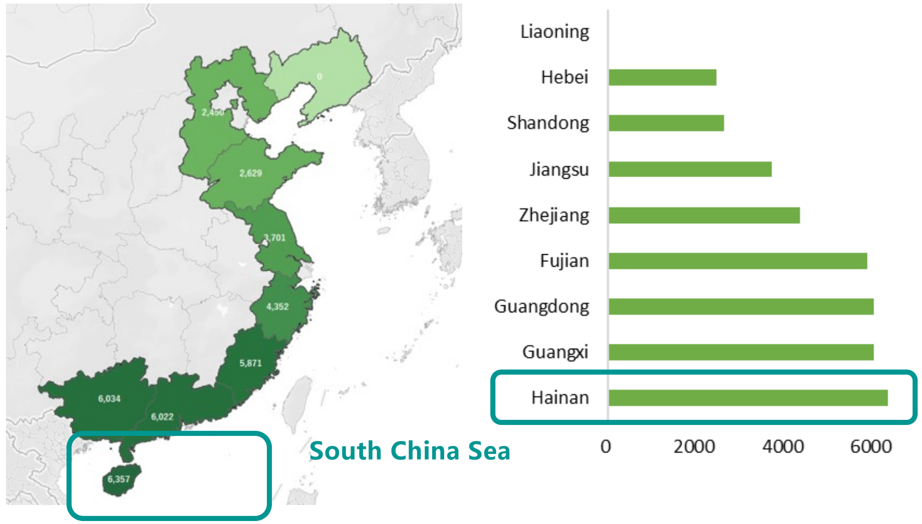



Annual highest tide level increment anomaly at Woody Island *(SOA, 2017)*

## High microalgae productivity

Used **microalgae biomass productivity growth model** to calculate the **theoretical yield of biofuel** in coastal areas of China




Theoretical annual yield of microalgae oil in coastal provinces of China（L·hm$^{-2}$）

# 3

# Inclusive Index Evaluation

# 3 Inclusive Index Evaluation: Method

- **Inclusive Impact Indicator (III)** (IMPACT Research Group, 2006)

  A metric developed to assess environmental sustainability and economic feasibility of ocean utilization technologies.

$$III = [(EF - BC) + \alpha ER] + \gamma [(C - B) + \beta HR] \quad (1)$$

$$III_{light} = (EF - BC) + \gamma (C - B) \quad (2)$$

$$III^{*}_{light} = \frac{EF + \gamma C}{BC + \gamma B} \quad (3)$$

$III_{light} < 0$: Sustainable
$III_{light} > 0$: Unsustainable

$III_{light}{}^{*} < 1$: Sustainable
$III_{light}{}^{*} > 1$: Unsustainable

$EF$: Ecological Footprint
$BC$: Biocapacity
$ER$: Ecological Risk
$HR$: Human Risk
$C$: Cost

$B$: Benefit
$\alpha$: Conversion Factors from ER to EF
$\beta$: Conversion Factors from HR to C
$\gamma$: Conversion Factors from Economic Value to Environmental Value

# 3 Inclusive Index Evaluation: Method

- **Ecological Footprint in the system**

$$EF = f_{forest} A_{forest} \left( \frac{E_{RM} + E_B + E_S}{n} + E_{OTEC} + E_{Microalgae} + E_{Tuna} \right)$$

$f_{forest}$: Equivalence factor for forest area, $f_{forest}$ = 1.26 gha/ha
$A_{forest}$: Estimated CO2 emissions are converted into a forest area, $A_{forest}$ = 0.19 ha/t-CO2
$E_{RM}$: CO2 emissions associated with raw-material production and transportation
$E_B$: CO2 emissions associated with building
$E_S$: CO2 emissions associated with scrapping
$E_{OTEC}$: CO2 emissions associated with operation of OTEC
$E_{Microalgae}$: CO2 emissions associated with operation of microalgae cultivation and processing
$E_{Tuna}$: CO2 emissions associated with operation of tuna aquaculture

# 3 Inclusive Index Evaluation: Method

- **Biocapacity (BC) changes in the system**

**(1) CO2 emissions avoidance through replacing the fossil fuel by producing algal biofuel**

$$BC_{Microalgae} = f_{forest} \times A_{forest} \times Annual\ Biofuel\ Production \times \text{ Unit CO2 Emission of Fossil Fuel}$$

**(2) Tuna production that could replace the piscatorial tuna catch**

$$BC_{Tuna} = f \times A \times Annual\ Tuna\ Production \times \text{ Unit CO2 emission to catch tuna in natural conditions}$$

(It will emit 12.6 tons of CO2 to catch 1 ton of tuna in natural conditions. )

**(3) Enhancement of marine primary production (ocean fertilization) by artificial upwelling DOW**

$$P_P = \alpha_{CN} M_C N_{DOW} Q_{DOW}$$

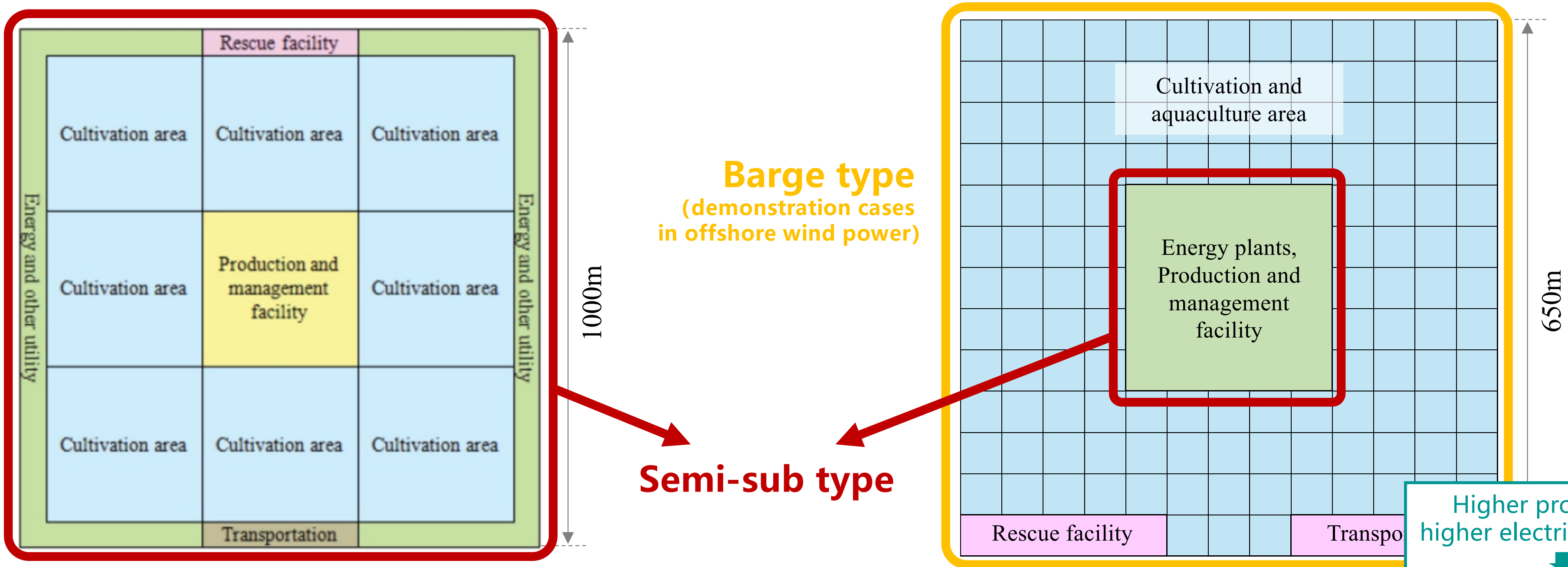
$$P_F = P_P {K_U}^{TL_U}$$

$$BC_{Fertilization} = f_{sea} \frac{P_F}{Y_{F_0}}$$

$P_P$: The annual primary production PP (t-C/y)
$\alpha_{CN}$: The C/N ratio of the phytoplankton, $\alpha_{CN}$=106/16 (the Redfield ratio)
$M_c$: The atomic weight of carbon, $M_c$ = 12 g/mol
$N_{DOW}$: The concentration of dissolved inorganic nitrogen in DOW (μM/ m3)
$Q_{DOW}$: Intake volume of DOW ($m^3$/y);
$P_F$: The annual fish production due to artificial upwelling (t-C/y)
$K_U$: Ecological efficiency, $K_U$ =0.2
$TL_U$: Trophic level, $TL_U$ =1.5
$Y_{F0}$: The average annual fish production in the productive sea area

(Otsuka, 2011)

# 3 Inclusive Index Evaluation: System design modification




| Platform Size | 1000m×1000m |
|---|---|
| Floating Structure | Semi-sub type |
| Microalgae System | Open raceway pond (38 g/m$^2$ day) |
| OTEC Scale | 2MW |

Original System

| Platform Size | 650m×650m |
|---|---|
| Floating Structure | Barge type (surrounding), semi-sub (c )) |
| Microalgae System | Photobioreactor (560 g/m$^2$ day) |
| OTEC Scale | 12.5MW |

Higher productivity, higher electricity demand
⬇
Smaller cultivation area to reach same yield

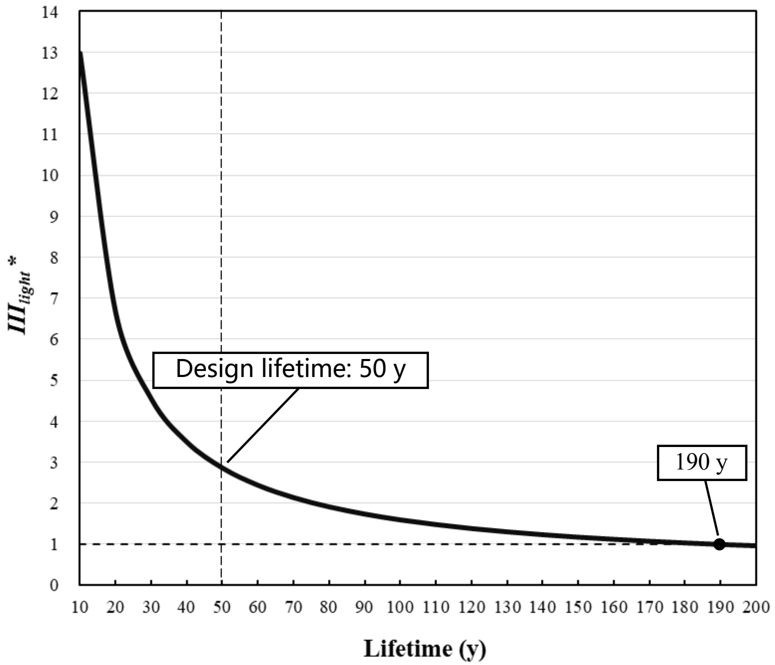
Modified System

# 3 Inclusive Index Evaluation: Results

- Lifetime dependence of Triple I light star of the two systems

$III_{light}^{*}<1$: Sustainable
$III_{light}^{*}>1$: Unsustainable

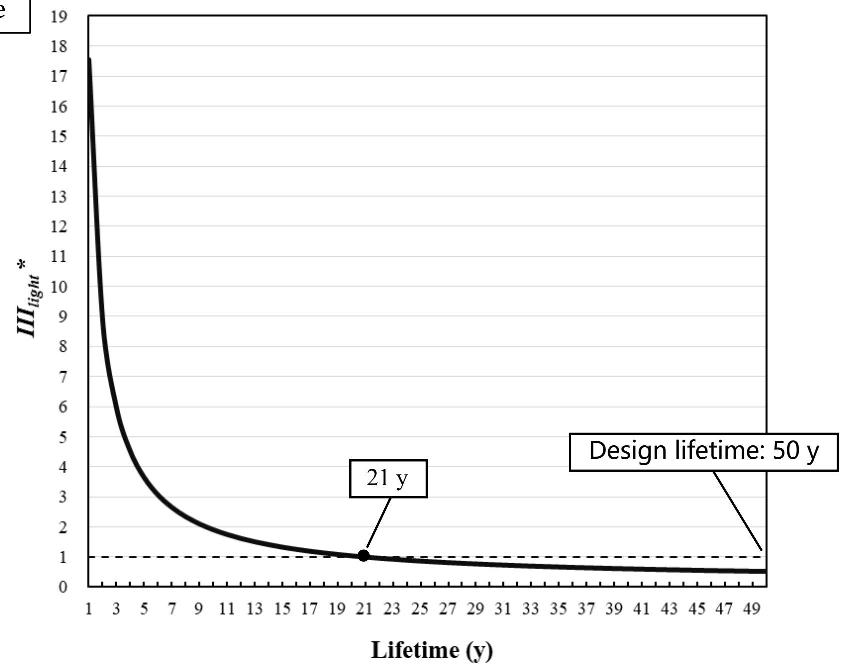
Original System




| Lifetime | *EF* | *BC* | Cost | Benefit | $III_{light}$ | $III_{light}^{*}$ |
|---|---|---|---|---|---|---|
| year | gha | gha | M Yen | M Yen | gha | |
| 50 | 18,421 | 12,517 | 21,563 | 6,647 | 77,416 | 2.85 |

**Unsustainable**

Modified System




| Lifetime | *EF* | *BC* | Cost | Benefit | $III_{light}$ | $III_{light}^{*}$ |
|---|---|---|---|---|---|---|
| year | gha | gha | M Yen | M Yen | gha | |
| 50 | 9,413 | 29,316 | 7,809 | 6,625 | -18,399 | 0.51 |

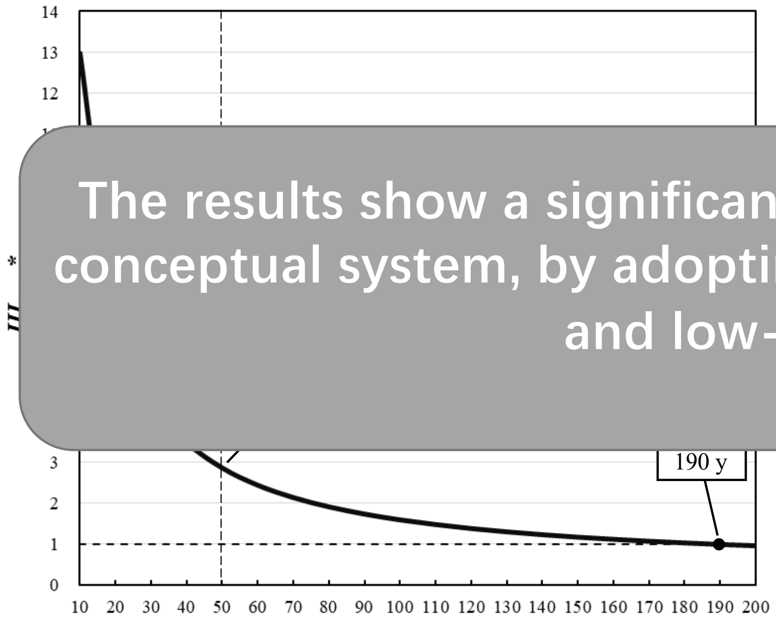
**Sustainable**

# 3 Inclusive Index Evaluation: Results

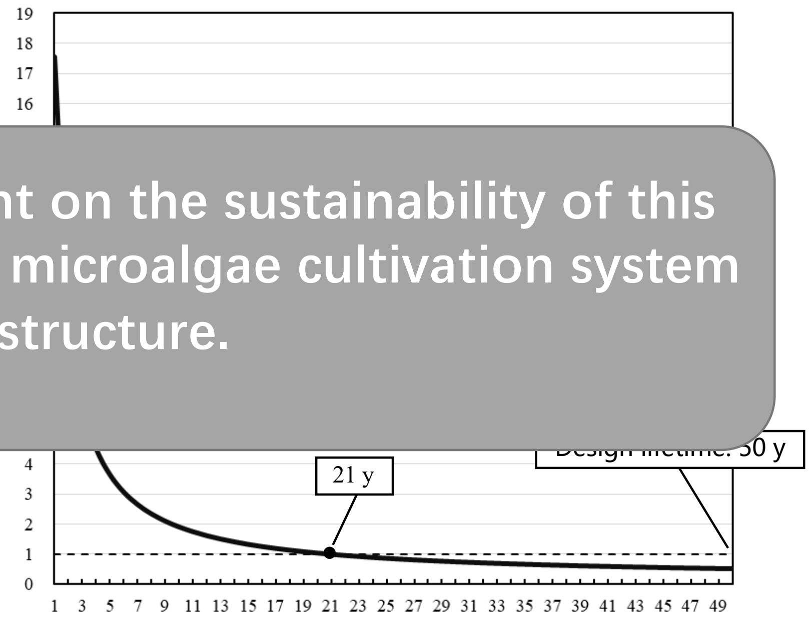
- **Lifetime dependence of Triple I light star of the two systems**

$III_{light}^{*}<1$: Sustainable
$III_{light}^{*}>1$: Unsustainable

Original System




Modified System




The results show a significant improvement on the sustainability of this conceptual system, by adopting high-yield microalgae cultivation system and low-cost floating structure.

| Lifetime | *EF* | *BC* | Cost | Benefit | $III_{light}$ | $III_{light}^{*}$ |
|---|---|---|---|---|---|---|
| year | gha | gha | M Yen | M Yen | gha | |
| 50 | 18,421 | 12,517 | 21,563 | 6,647 | 77,416 | 2.85 |

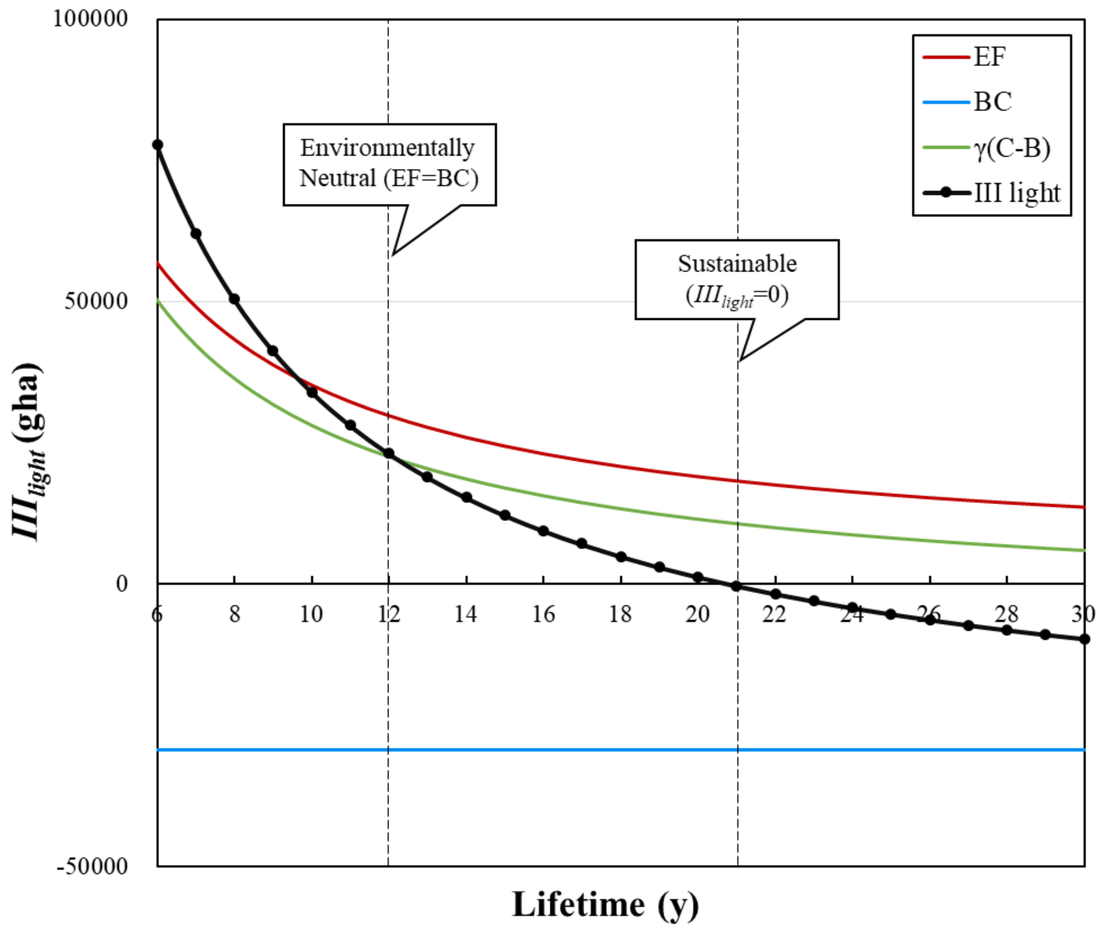
**Unsustainable**

| Lifetime | *EF* | *BC* | Cost | Benefit | $III_{light}$ | $III_{light}^{*}$ |
|---|---|---|---|---|---|---|
| year | gha | gha | M Yen | M Yen | gha | |
| 50 | 9,413 | 29,316 | 7,809 | 6,625 | -18,399 | 0.51 |

**Sustainable**

# 3 Inclusive Index Evaluation: Results

**Triple I light of the modified system**




**At the lifetime of 12 years,**

$EF = BC$ environmentally neutral

**At the lifetime of 21 years,**

$(EF - BC) + \gamma(C - B) = 0$ sustainable

**At the design lifetime (50 year),**

| Lifetime | *EF* | *BC* | Cost | Benefit | $III_{light}$ |
|---|---|---|---|---|---|
| year | gha | gha | Million Yen | Million Yen | gha |
| 50 | 9,413 | 29,316 | 7,809 | 6,625 | -18,399 |

$III_{light}<0$: New conceptual system is **sustainable**.

C > B: At least 15% of the cost should be cut off to make it **profitable**.

# 4

# Environmental Impact Simulation

# 4 Environmental Impact Simulation: Method

MEC Model (3D fluid) + Sessile Organism Model + Pelagic Ecosystem Model

# 4 Environmental Impact Simulation: Method

MEC Model (3D fluid) + Sessile Organism Model + Pelagic Ecosystem Model

Governing equations for the tidal flow:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho_0}\frac{\partial p}{\partial x}+fv+A_M\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\frac{\partial}{\partial z}\left(K_M\frac{\partial u}{\partial z}\right)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho_0}\frac{\partial p}{\partial y}+fv+A_M\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{\partial}{\partial z}\left(K_M\frac{\partial v}{\partial z}\right)$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho_0}\frac{\partial p}{\partial z}+fv+A_M\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}\right)+\frac{\partial}{\partial z}\left(K_M\frac{\partial w}{\partial z}\right)-\frac{\rho-\rho_0}{\rho_0}g$$

Advection and velocity equation for temperature and salinity:

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=A_c\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\frac{\partial}{\partial z}\left(K_c\frac{\partial T}{\partial z}\right)+q_{Tmp}$$

$$\frac{\partial S}{\partial t}+u\frac{\partial S}{\partial x}+v\frac{\partial S}{\partial y}+w\frac{\partial S}{\partial z}=A_c\left(\frac{\partial^2 S}{\partial x^2}+\frac{\partial^2 S}{\partial y^2}\right)+\frac{\partial}{\partial z}\left(K_c\frac{\partial S}{\partial z}\right)+q_{Sal}$$

（日本造船学会海洋環境研究委員会, 2006）

# 4 Environmental Impact Simulation: Method

MEC Model (3D fluid) + **Sessile Organism Model** + Pelagic Ecosystem Model

The adhering organism (ADH) change on the floating structure:

$$\frac{\partial ADH}{\partial t} = B_{101} - B_{102} - B_{103}$$

Water quality change caused by grazing of ADH:

$$\frac{\partial X}{\partial t} = (Time\ change\ term\ of\ pelagic\ ecosystem\ model) - \frac{B_{101} \times X}{h \times (PHY + ZOO + POC)}$$

Water quality change caused by breath, egestion, and mortality of ADH:

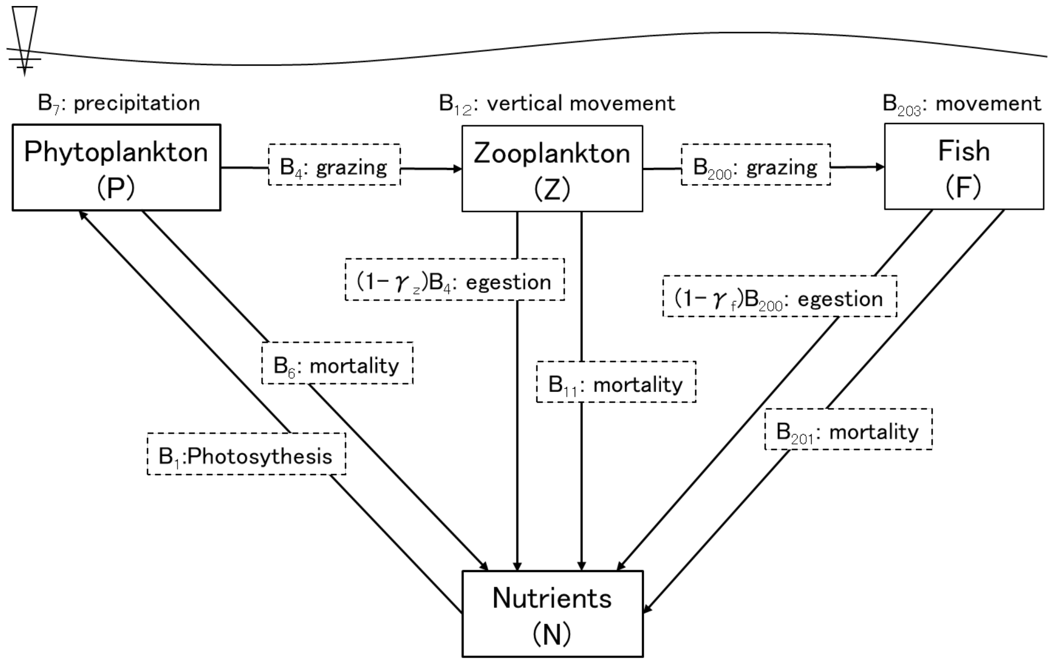
$$\frac{\partial X}{\partial t} = (Time\ change\ term\ of\ pelagic\ ecosystem\ model) + \frac{[X:C] \times (B_{102} + B_{103r})}{h}$$

($B_{101}$: grazing; $B_{102}$: breath; $B_{103}$: egestion and mortality; $B_{103r}$: mortality)

(Kitazawa, 2001)

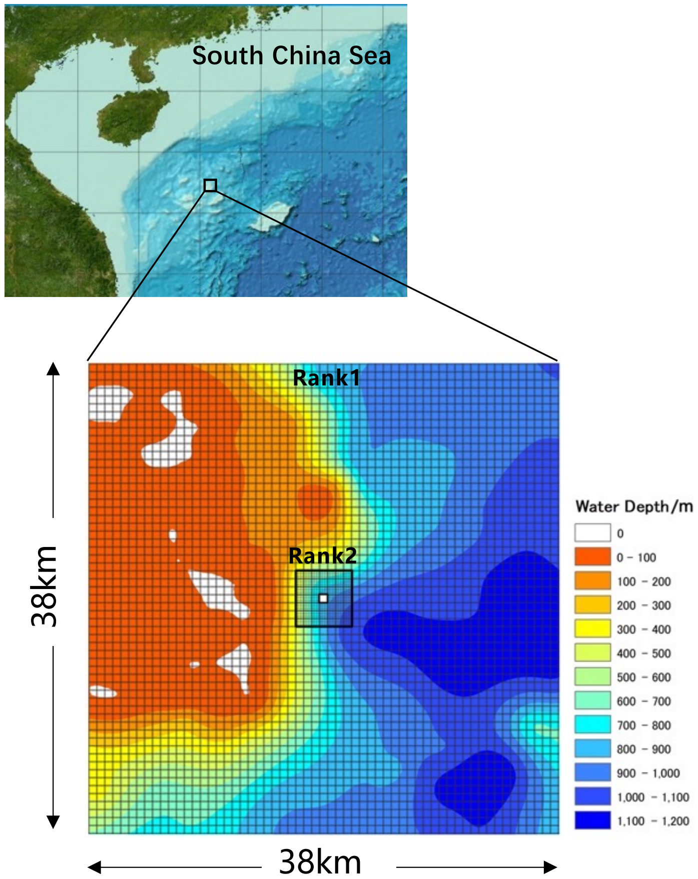
# 4 Environmental Impact Simulation: Method

MEC Model (3D fluid) + Sessile Organism Model + Pelagic Ecosystem Model




NPZF Ecosystem Model

# 4 Environmental Impact Simulation: Computational conditions




Bathymetric distribution of computational area

**Computational domain:**
The surrounding sea areas of Woody Island

**Floating Structure Size:** 650m

**Grid Size:** rank1 650m (59×59×26)
rank2 217m (21×21×26)

**Period:** August 1$^{st}$ – 31$^{th}$ , 2019 (one-month simulation)

**Data Source:**

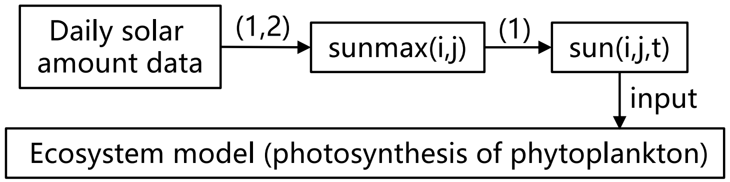
| | |
|---|---|
| Topography | Gebco 2019 |
| Water Quality | WOA 2018, CMEMS, etc. |
| Meteorology | China Meteorological Administration (CMA) |
| Ocean current | CMEMS |

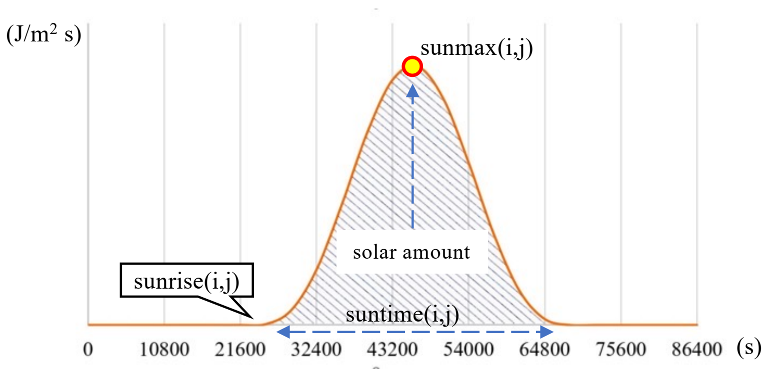
**Discharged deep sea water conditions:**

| | |
|---|---|
| Intake depth | 800m |
| Discharged depth | 30m |
| Discharged amount | 62.5$m^3$/s (12.5MW) |
| Nitrate Concentration | 33.68 mmol/$m^3$ |

# 4 Environmental Impact Simulation: Computational conditions

## ・Solar Radiation Adjustment



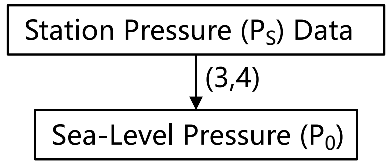




Solar Radiation Variation Formula (Ikushima,1967):

$$\mathrm{sun(i,j,t)} = \mathrm{sunmax(i,j)} \times \sin^3\{\frac{\pi}{\mathrm{suntime(i,j)}} \times (\mathrm{t} - \mathrm{sunrise(i,j)})\} \quad (1)$$

$$\text{solar amount} = \int_{\mathrm{sunrise(i,j)}}^{\mathrm{sunrise(i.j)+suntime(i,j)}} \mathrm{sun(i,j,t)}\,\mathrm{dt} \quad (2)$$

## ・Air Pressure Adjustment




$$P_0 = P_s \times 10^{\frac{h}{18400(1+\frac{T_m}{273})}} \quad (3)$$

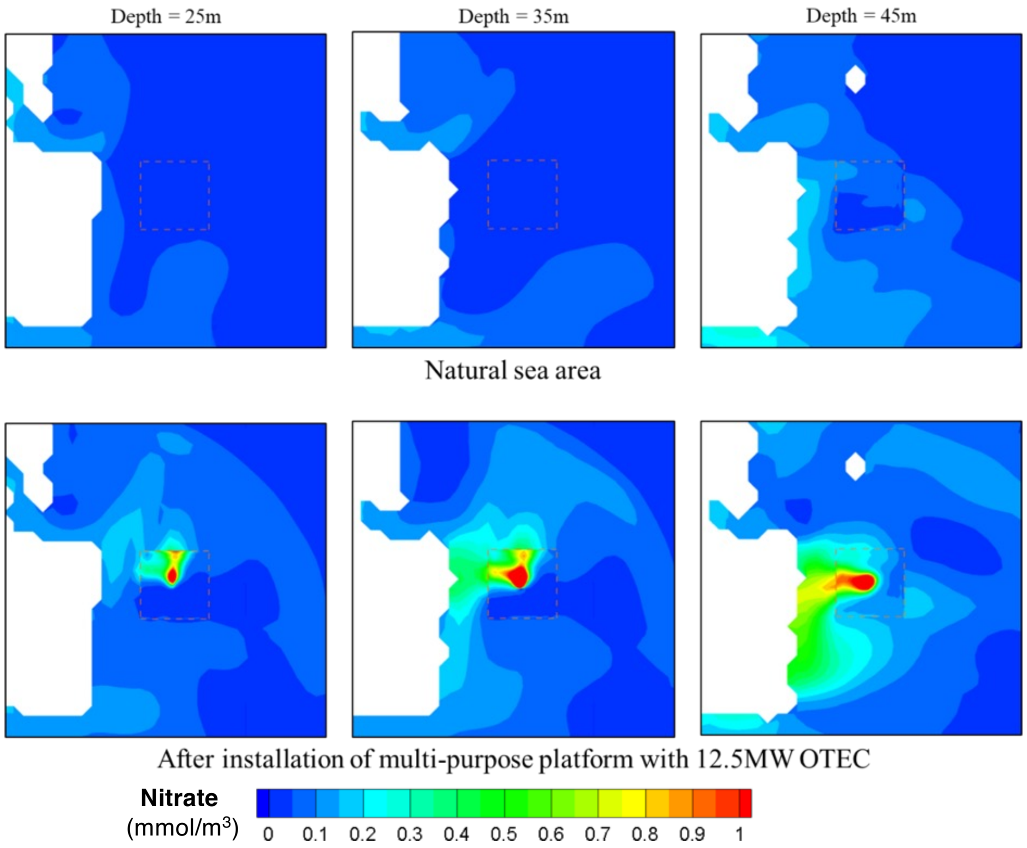
$$T_m = \frac{t + t_{12}}{2} + \frac{h}{400} \quad (4)$$

## ・Water Quality Adjustment

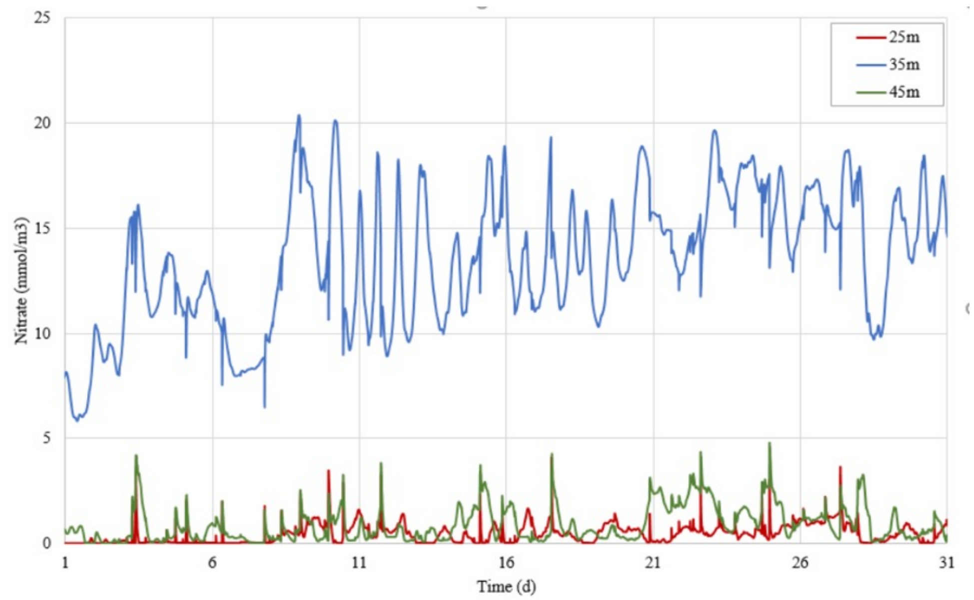
$$\mathrm{PHY:ZOO} = 29.51:1$$

# 4 Environmental Impact Simulation: Results

- **Differences in nitrate due to the multi-purpose platform**




Spatial distribution of nutrient

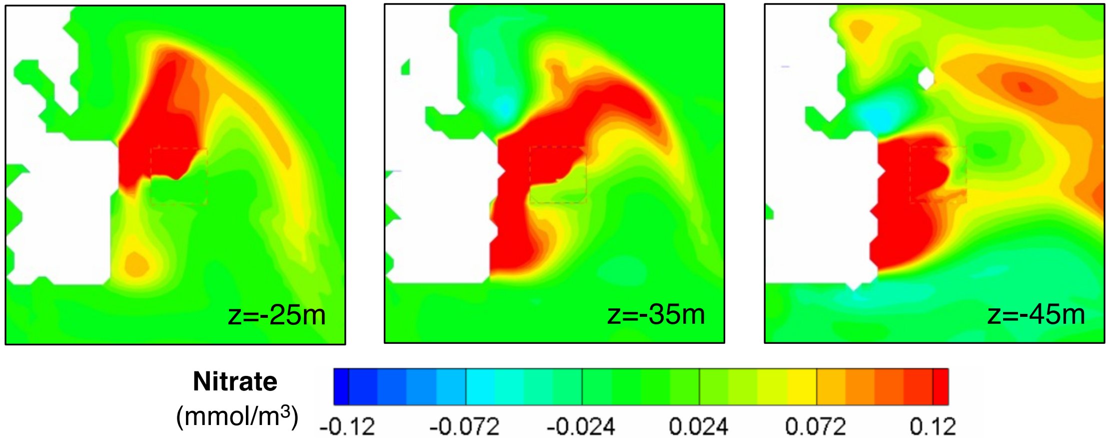


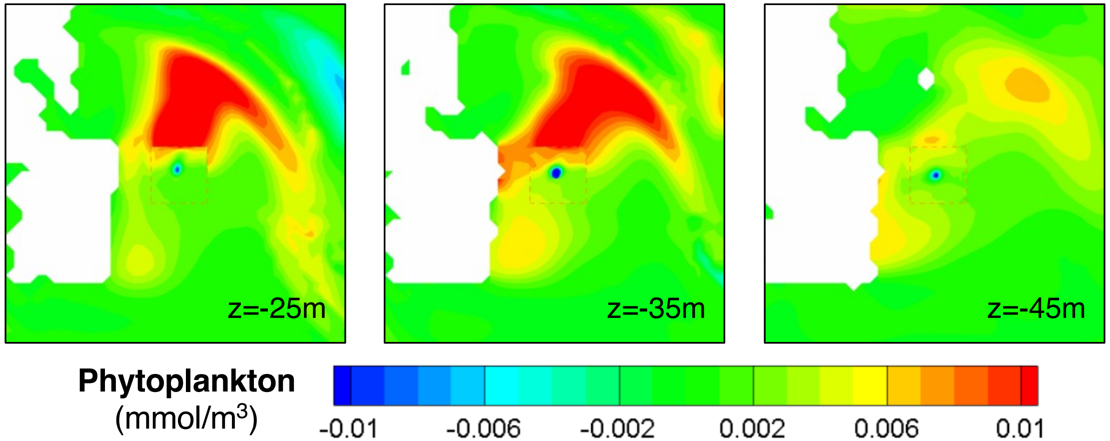

Nitrate concentration after platform installation at the discharged point

**The most affected area is at 35m depth.**

# 4 Environmental Impact Simulation: Results

- **Subtraction between the results of before and after the platform installation**




**Nitrate Concentration:**

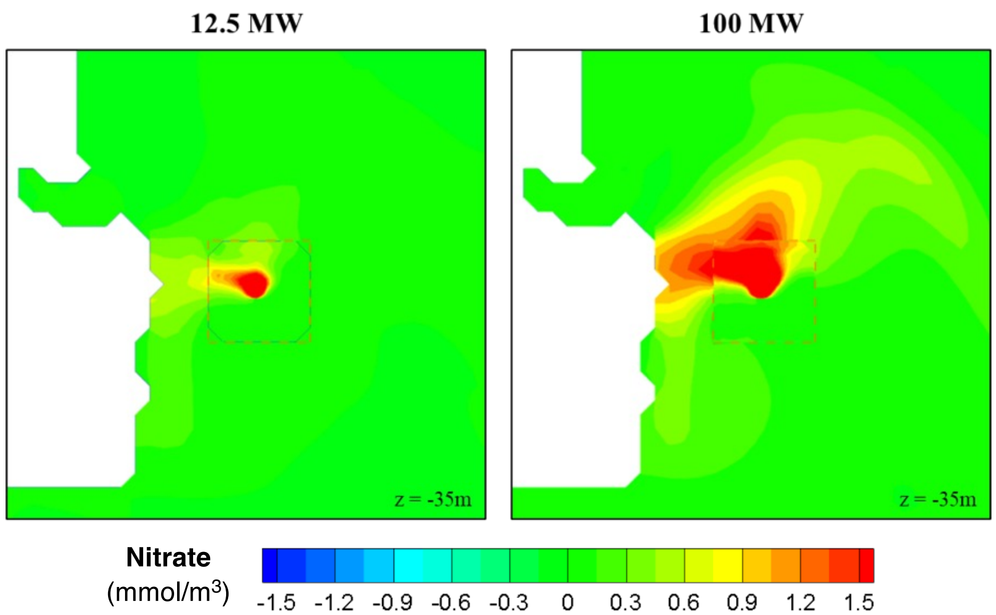
- Nitrate increases notably at 35m depth, especially at the discharged point.
- It enhances greatly because the upper layer of seawater in natural conditions consists of little nitrate concentration.

**Phytoplankton density:**

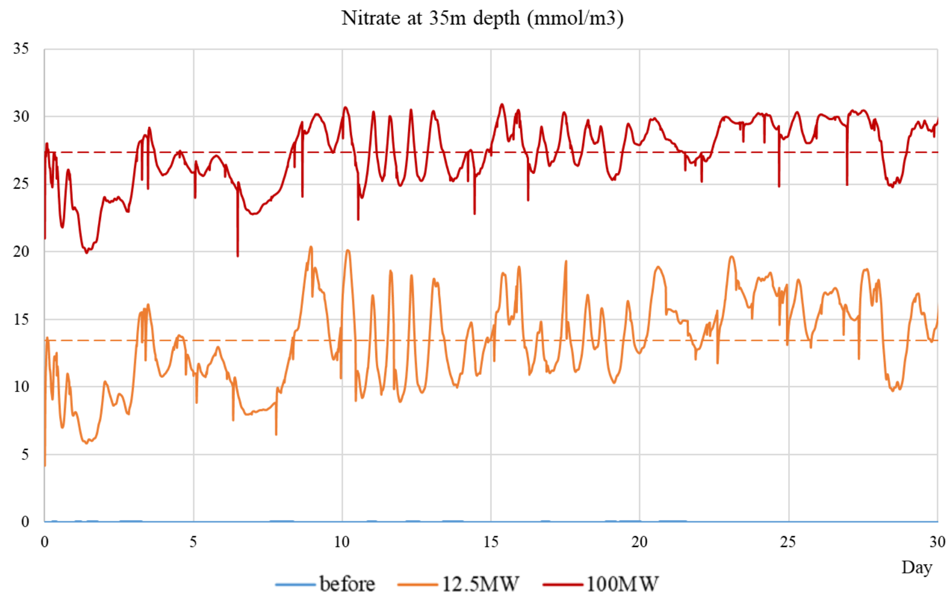
- Density at the discharged point decreased because of the low water temperature and low plankton concentration in deep ocean water.
- In the places that have some distance from the discharged point, phytoplankton increased visibly, because of the overall nutrient level increase in the sea area.

# 4 Environmental Impact Simulation: Results

- **Different scales of OTEC**




Changes of NUT in horizontal plane due to different OTEC scales




Time series results of nutrient concentration after the installation of platform with different OTEC scales

5

# Fertilization effect of deep ocean water (DOW)

# 5 Fertilization effect of DOW: Method

- **Previous Method: BC changes by enhancing marine productivity**

primary production increase $P_P$ → fish production increase $P_F$ → $BC_{fertilization}$

$$P_P = \alpha_{CN} M_C N_{DOW} Q_{DOW}$$

Assume all nutrients increase would contribute to the primary production increase.

Assume all nutrient in DOW contribute to the nutrient increase in target area.

**Overestimation**

- **New Method: replacing the parameters with the simulation results**

Method 1: replace the nutrient term $N_{DOW}Q_{DOW}$ with the total nutrient concentration increase.
Method 2: replace the primary production term $P_P$ with the plankton concentration increase.

The total parameter concentration change in the simulation results:

$$Q_i = \overline{\Delta C_i} \times V_i \times 1000$$

$\overline{\Delta C_i}$ (mmol/m$^3$): the average parameter concentration change in each grid in a certain period
$V_i$ (m$^3$): the volume of each grid

# 5 Fertilization effect of DOW: Results

Comparison of 3 methods to calculate $BC_{fertilization}$

| | Previous method | New method 1 (Replace N) | New method 2 (Replace P) |
|---|---|---|---|
| Nutrient increase | $5.72 \times 10^7$ mol | $1.92 \times 10^7$ mol | ¥ |
| Primary production ($P_P$) | 4550.58 t-C/y | 1524.03 t-C/y | 87.60 t-C/y |
| Estimate fish production ($P_F$) | 407.02 t | 136.31 t | 7.84 t |
| *BC* by ocean fertilization | 20630 gha | 6909 gha | 397 gha |

$III_{light}$ result of the modified system using 3 methods

| | ***EF*** (gha) | ***BC*** (gha) | **Cost** (M Yen) | **Benefit** (M Yen) | $III_{light}$ (gha) |
|---|---|---|---|---|---|
| Previous method | 9402 | 31210 | 7809 | 6625 | -20304 |
| New method 1 | 9402 | 17489 | 7809 | 6625 | -6583 |
| New method 2 | 9402 | 10977 | 7809 | 6625 | -71 |

- **Replace N**: simulated nutrient increase will be only about 1/3 of the nutrient in DOW, as well as the $Bc_{fertilization}$.
- **Replace P:** even lower primary production, which results in a BC change that is very small comparing to the previous value.
- The conclusion that the modified system has the sustainability does not change.

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# Summary

# 6 Summary

## Conclusion

- Improved the **conceptual system design** of an offshore multi-purpose platform and confirmed a proper site for it.
- evaluated the **economic and environmental sustainability** of the original and the modified systems using the inclusive index, and confirmed the effectiveness of modification.
- conducted further **environmental impact simulation by numerical modeling**, and successfully simulated the environmental impact on the water quality and ecosystem of the offshore multi-purpose platform.
- **Introduced the simulation results into the inclusive index evaluation**, reestimated the biocapacity by the ocean fertilization effect, and it is proved that the modified system is sustainable.

## Future works

- **Inclusive Index Evaluation**: Since there are few commercialized cases of the offshore multi-purpose system for reference, the veracity of some items in the cost estimation still has room for improvement.
- **Numerical simulation:** Some parameters might need to be further adjusted according to the real observation data.