Design Improvement and Sustainability Assessment of a Conceptual Multi-purpose Offshore Platform

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1 Introduction

Introduction: Research background

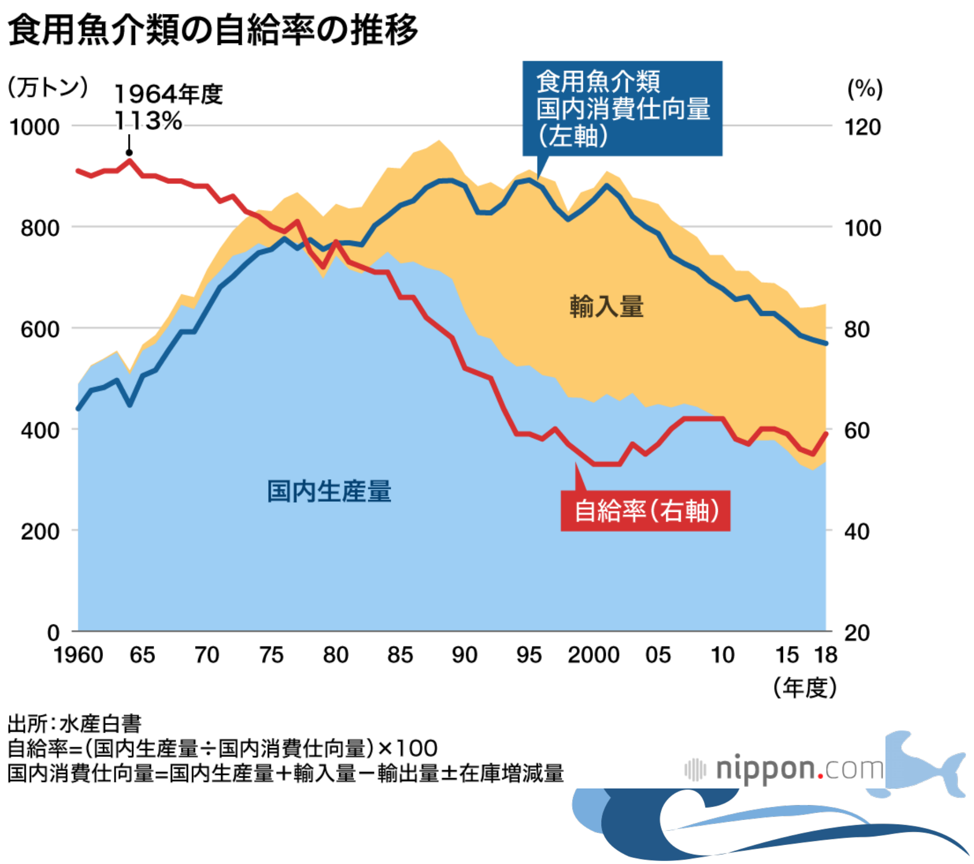
Ocean Thermal Energy Conversion (OTEC)

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.

Japan's self-sufficiency rate for edible seafood



Introduction: Previous study

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

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

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

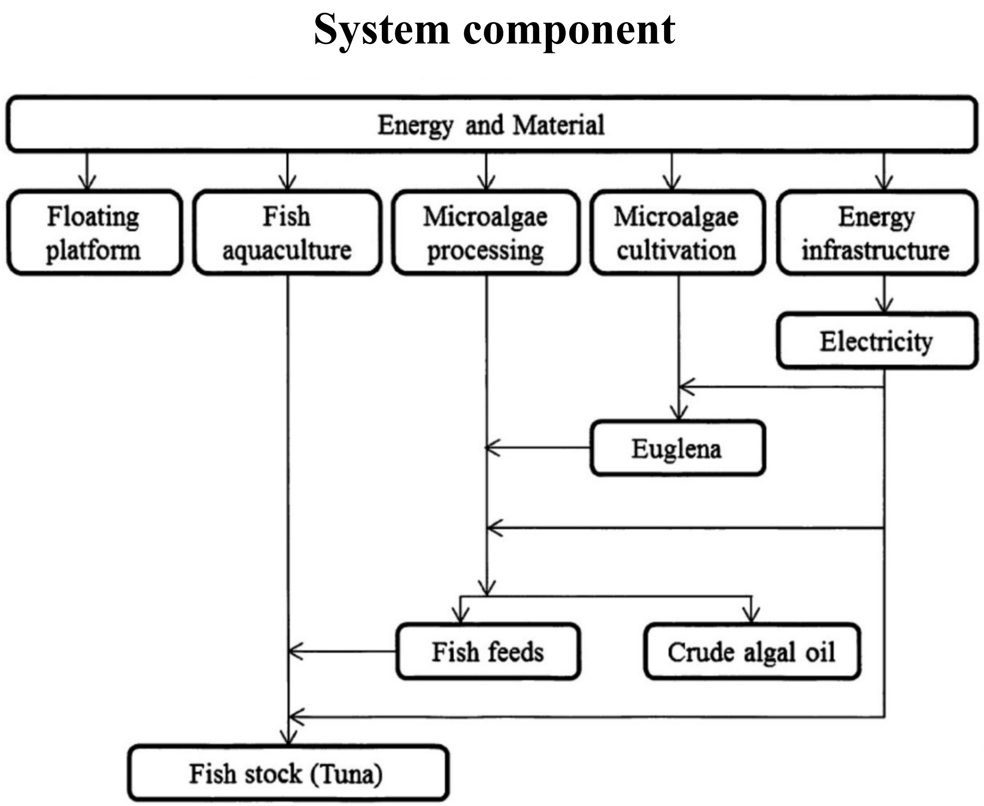
$III_{light}<0$: Sustainable
$III_{light}>0$: Unsustainable

$$III_{light}{}^{*} = \frac{EF + \gamma C}{BC + \gamma B}$$

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

EF: Ecological Footprint
BC: Biocapacity
C: Cost
B: Benefit
γ: Environmental Economic coefficient ($EF_{regional}/GDP_{regional}$)

Introduction: Previous study



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

- This system can develop marine renewable energy for productive activities.
- The platform not dependent on electricity and energy from the land.
- Microalgae cultivation can help reduce CO_2 emissions.
- It can increase the production of aquaculture fish and improve the rate of fish self-sufficiency in Japan.
- But the system is **unsustainable**.

Introduction: Previous study

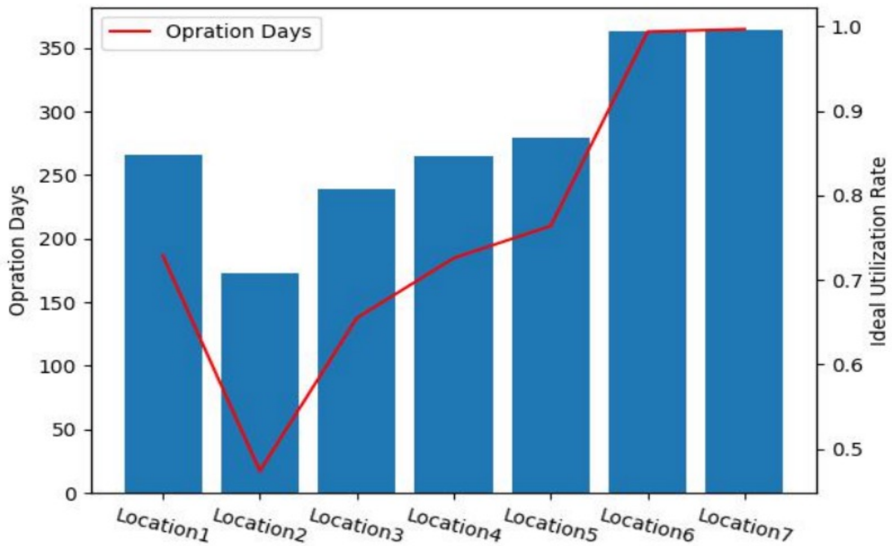
The differences between the original system and the modified system *(Chen, 2020)*

	The original system	The modified system
Platform size	1000m×1000m	650m×650m
Microalgae cultivation system	Open raceway pond	Photobioreactor
Floating structure	Semi-sub type	Barge type (surrounding) Semi-sub (center)
OTEC scale	2MW	12.5MW

- Chen reduced the cost and the impact of the system on the environment.
- The system became sustainable with modifications, but it is **unprofitable**.
- In the inclusive index, changes in Biocapacity due to ocean fertilization may be overestimated, and only the environmental impact of CO_2 emissions is considered.

Introduction: Previous study

The operation days and rate of OTEC platform in the target regions



Location 1 Ogasawara Islands region
Location 2 The south coastal of Kochi prefecture
Location 3 The south coastal of Kagoshima prefecture
Location 4 The Amami Oshima Islands region
Location 5 Kumejima Islands region
Location 6 The East coast of Sulu Sea of the Philippines
Location 7 Pujada Bay in the Philippines.

Site assessment of multi-purpose offshore platform with OTEC *(Ding, 2022)*

- In subtropical areas, the seasonal surface sea water temperature limits the operation days of the system, thus affecting its economic feasibility.
- If the platform is implemented in the Ogasawara sea area, it will increase employment opportunities in the Ogasawara Islands and improve the utilization of Japanese marine resources.

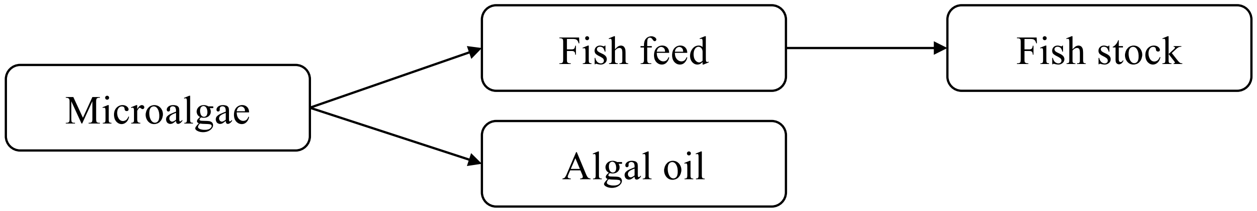
Introduction: Objectives

- Improve the conceptual system design of the offshore multi-purpose platform to increase the economic benefit and ecological value of the multi-purpose platform;
- Consider more reasonable evaluations for Ecological Footprint and Biocapacity in the inclusive index;
- Assess economic and environmental sustainability using the inclusive index.

2 Improvement of Multi-purpose Offshore Platform

Improvement of Multi-purpose Offshore Platform: System

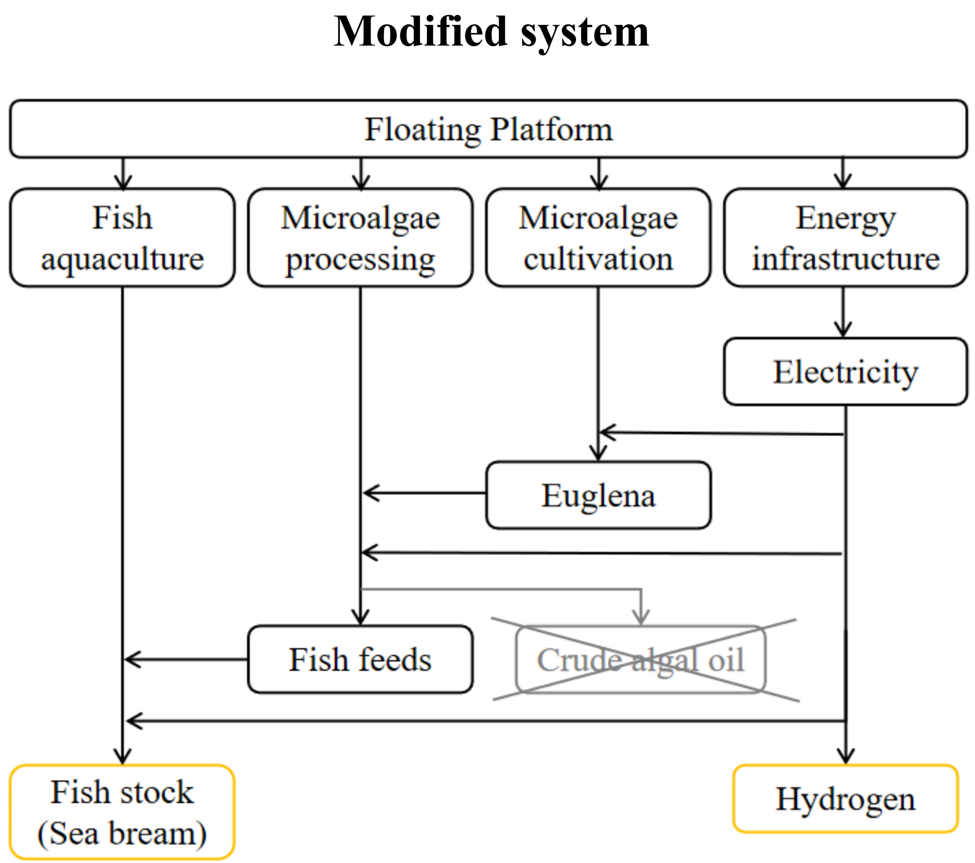
Production process in original system



Input	Output	Price	Benefit
1000 kg Microalgae	285kg Algal oil	74 Yen/kg *(Duan, 2015)*	21090 Yen
1000 kg Microalgae	513kg Sea bream	1500~2000 Yen/kg *(SAKAMA.inc)*	769500~1026000 Yen

- Replacing biofuel production with fish feed production will generate more fish production, resulting in increased economic benefits.
- Feed conversion ratio of tuna: 7~10 *(Chen, 2020)* Feed conversion ratio of sea bream: 2.5 *(Kallitsis, 2020)*
- The feed conversion ratio of seabream is lower than that of tuna. So changing aquaculture fish to sea bream can increase fish production, resulting in the platform generating more economic benefits.

Improvement of Multi-purpose Offshore Platform: System



- Removing the algae oil production part allows more fish feed to be produced from microalgae, resulting in increased aquaculture production.
- The aquaculture fish is changed from tuna to sea bream.
- A component for hydrogen production from excess electricity is added.
- These improvements will create more economic benefits.

Improvement of Multi-purpose Offshore Platform: System

Nutritional content of feed ingredient

Feed ingredient	Protein (%)	Lipid (%)	Carbohydrate (%)	References
Anabaena cylindrica	43–56	4–7	25–30	(Becker, 2007)
Botryococcus braunii	39.9	34.4	18.5	(Tavakoli et al., 2021)
Chlamydomonas rheinhardii	43–56	14–22	2.9–17	(Becker, 2007)
Chlorella pyrenoidosa	57	2	26	(Becker, 2007)
Chlorella vulgaris	51–58	14–22	12–17	(Becker, 2007)
Dunaliella salina	49–57	6–8	4–32	(Becker, 2007)
Euglena gracilis	39–61	14–20	14–18	(Becker, 2007)
Nannochloropsis granulata	33.5	23.6	36.2	(Tibbetts et al., 2017)

Potential of microalgae as a sustainable feed ingredient for aquaculture *(Nagappan, 2021)*

Proximate composition of the no fishmeal feed for sea bream

Proximate composition	
Protein (% Dry matter)	48.7
Lipid (% Dry matter)	15.2
Moisture (%)	23.0
Ash (% Dry matter)	6.5
Taurine (mg/g Dry matter)	5.45

Study on the effectiveness of fishmeal-reduced feeds for sea bream *(Matsukura, 2016)*

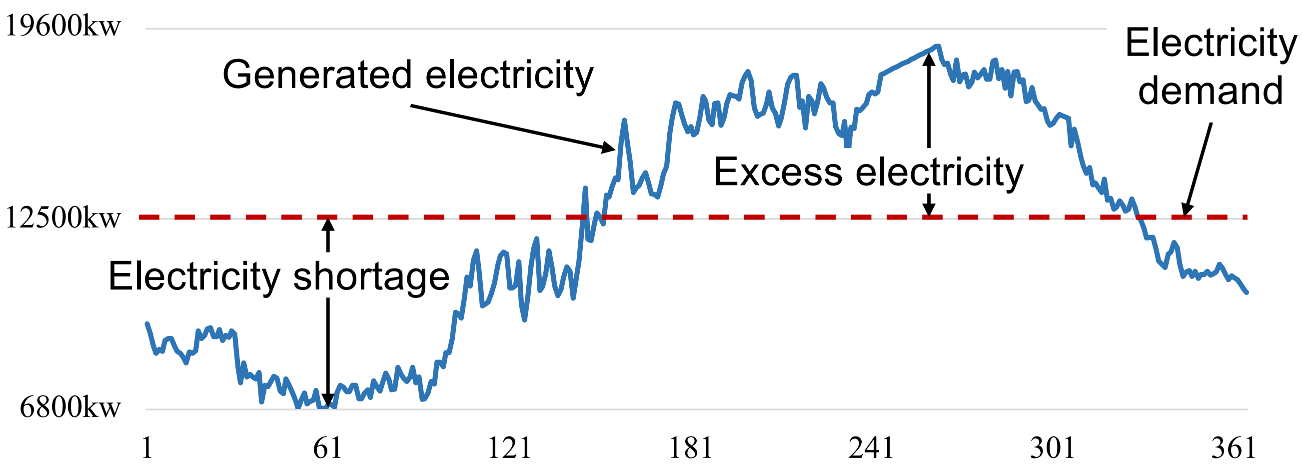
- The nutritional composition of Euglena is very similar to that of the no fishmeal feeds for sea bream.
- With the addition of only some water, Euglena can be used entirely to produce fish feed.
- Fish feed production will increase, leading to an increase in aquaculture production.

Improvement of Multi-purpose Offshore Platform: Energy

Electricity consumption of the multi-purpose platform

Electricity consumption for microalgae cultivation	12500 kW
Electricity consumption for feed production	78.2 kW/t-feed
Electricity consumption for fish aquaculture	1060 kW/t-fish
Heat consumption	3.1 MJ/kg-algae
Electricity consumption for the residence of staffs	0.16 GWh

12.5MW OTEC annual electricity generation change in Ogasawara sea area

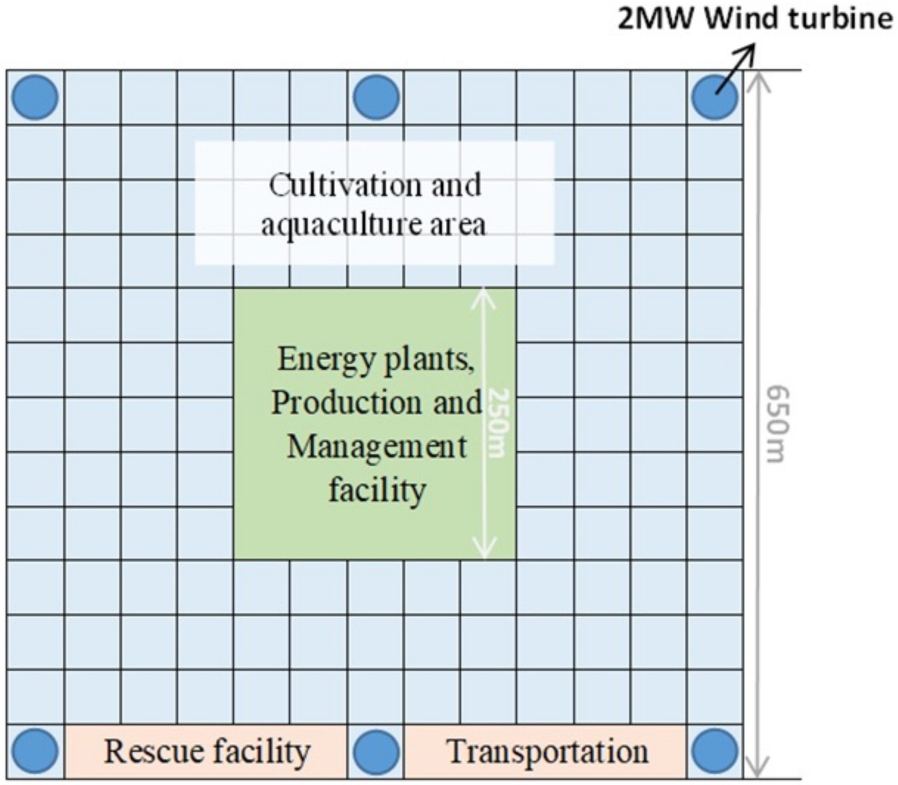


- The minimum surface water temperature in the Ogasawara Islands is 20°C during the year *(Ding, 2022).*
- At a surface water temperature of 20°C, the 12.5MW OTEC generation power is about 6800kw *(Okinawa Prefectural Government, 2014).*
- When the surface seawater temperature rises in summer, the platform will generate excess electricity can be used to produce hydrogen.

Improvement of Multi-purpose Offshore Platform: Energy

Plan 1：Multi-energy complementary system with 6×2MW wind turbines*

Layout of the multi-purpose platform system with 6×2MW wind turbines



Electricity consumption of the system with 6×2MW wind turbines

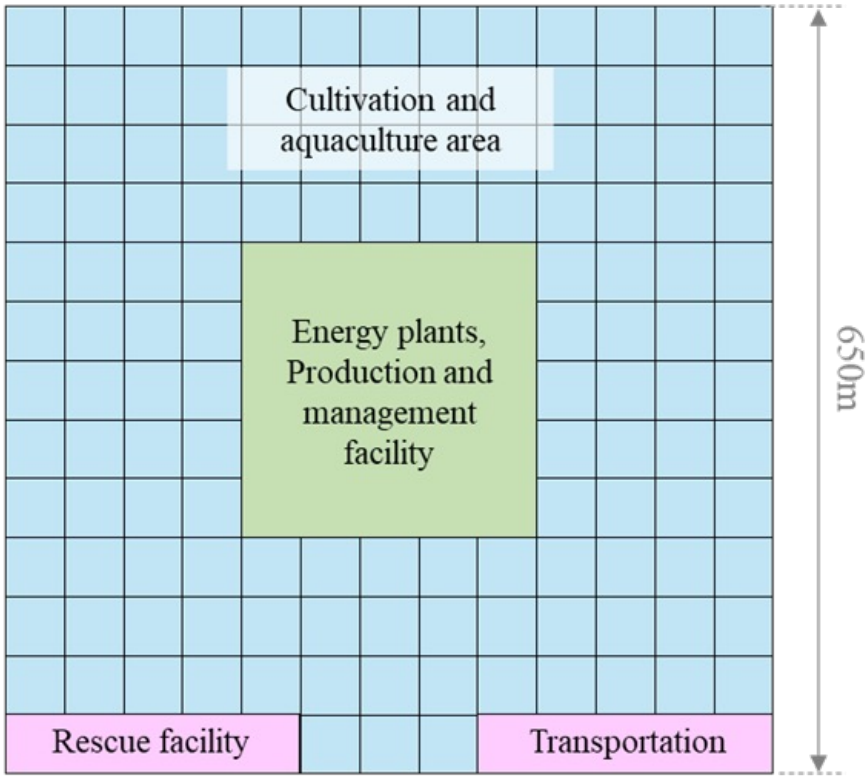
Annual total electricity consumption	128 GWh
OTEC Scale	12.5 MW
Wind turbines (6 units)	12 MW
Total annual electricity generation	155 GWh
Annual excess electricity	27 GWh

* Vestas V80 2MW wind turbine *(Noori, 2015)*

Improvement of Multi-purpose Offshore Platform: Energy

Plan 2: Increase in the OTEC scale

Layout of the multi-purpose platform system with 23MW OTEC



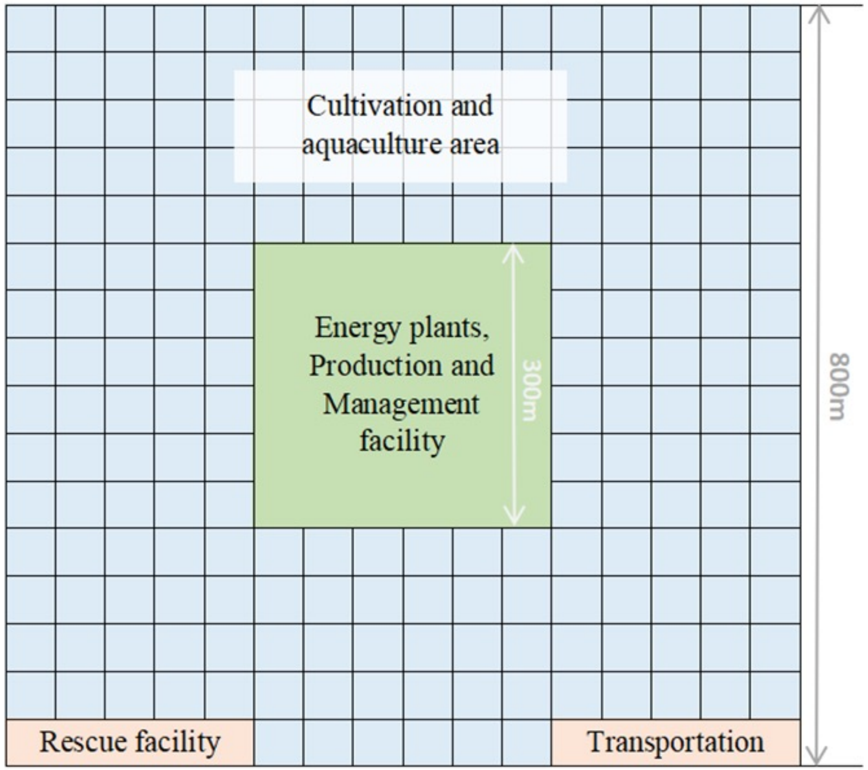
Electricity consumption of the system with 23MW OTEC

Annual total electricity consumption	128 GWh
OTEC Scale	23 MW
Total annual electricity generation	189 GWh
Annual excess electricity	61 GWh

Improvement of Multi-purpose Offshore Platform: Energy

Plan 3: Enlargement of the platform size

Layout of the multi-purpose platform system with enlarged platform size



Electricity consumption of the system with enlarged platform size

Basic electricity consumption	26250 kW
Annual total electricity consumption	258 GWh
OTEC Scale	50 MW
Total annual electricity generation	410 GWh
Annual excess electricity	152 GWh

Improvement of Multi-purpose Offshore Platform: Productions

Production scale of the original system

Items	Value	Units
Days of operation	266	d/y
Fish feed	24000	t/y
Feed conversion ratio (Tuna)	10	
Fish stock (Tuna)	2400	t/y
Algal oil	1963	t/y
Benefit of Algal oil	145	M Yen
Benefit of Tuna	6480	M Yen

The production scale of modified systems

Items	System with 6×2MW wind turbines	System with 23MW OTEC	System with enlarged platform size
Days of operation	360 d/y		
Fish feed	16467 t/y		25806 t/y
Feed conversion ratio (Sea bream)	2.5		
Fish stock (Sea bream)	6587 t/y		10322 t/y
Hydrogen	482 t/y	1089 t/y	2714 t/y
Benefits of Hydrogen	578.4 M Yen	1306.8 M Yen	2356.8 M Yen
Benefits of Sea bream	9880.5~13174 M Yen		15483~20644 M Yen

	Original System	System with 6×2MW wind turbines	System with 23MW OTEC	System with enlarged platform size
Total Cost (Million Yen)	8215	8489~8531	5662~8731	11024~11196
Total Benfit (Million Yen)	6625	10458.9~13752.4	11187.3~14480.8	18739.8~23900.8

Modified platforms are all **profitable** compared to the original platform.

3 Inclusive Index Evaluation

Inclusive Index Evaluation

Triple I: $III_{light} = (EF - BC) + \gamma(C - B)$ $\qquad III_{light}{}^{*} = \dfrac{EF + \gamma C}{BC + \gamma B}$

Ecological Footprint in the system

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

f_{forest}: Equivalence factor for forest area, f_{forest} = 1.26 gha/ha
A_{forest}: Estimated CO_2 emissions are converted into a forest area, A_{forest} = 5.2 t-CO_2/ha/year
E_{RM}: CO_2 emissions associated with raw-material production and transportation
E_B: CO_2 emissions associated with building
E_S: CO_2 emissions associated with scrapping
E_{OTEC}: CO_2 emissions associated with operation of OTEC
E_{Wind}: CO_2 emissions associated with operation of wind turbines
$E_{Microalgae}$: CO_2 emissions associated with operation of microalgae cultivation and processing
E_{Fish}: CO_2 emissions associated with operation of fish aquaculture
EF_W : Ecological footprint of aquaculture waste treatment
n: Number of years of the platform operation

Inclusive Index Evaluation

Ecological footprint of aquaculture waste treatment

One of the significant environmental impacts of aquaculture is the discharge of organic matter and nutrients. In coastal aquaculture systems, the ecological footprint of aquaculture waste treatment can be calculated as:

$$EF_W = f_{sea} \times \frac{\text{Carbon content in aquaculture waste}}{P_{P_{coastal}}}$$

f_{sea}: Equivalence factor for marine area, f_{sea} = 0.37 gha/ha
$P_{P_{coastal}}$: Primary productivity in the coastal area, $P_{P_{coastal}}$ = 100 (g-C/m^2/year)

Since the multi-purpose platform is an offshore aquaculture system, these aquaculture wastes are probably carried by ocean currents. But the portion that is carried away is difficult to quantify. So it is assumed to be between zero and the ecological footprint of coastal aquaculture waste treatment.

Inclusive Index Evaluation

Biocapacity (BC) changes in the system

1. **CO2 emissions avoidance through replacing the fossil fuel by producing hydrogen**

$$BC_{Microalgae} = f_{forest} \times A_{forest} \times Annual\ Biofuel\ Production \times Unit\ CO_2\ Emission\ of\ Fossil\ Fuel$$

2. **Fish production that could replace the piscatorial sea bream catch**

$$BC_{Fish} = f_{forest} \times A_{forest} \times Annual\ Fish\ Production \times Unit\ CO_2\ emission\ to\ catch\ fish\ in\ natural\ conditions$$

Inclusive Index Evaluation

Biocapacity (BC) changes in the system

3. Enhancement of marine primary production (ocean fertilization) by nutrients supply in DOW

It can be assumed that all nutrients from deep ocean water will lead to increases in primary production wherever it is transported. The BC changes can be calculated as:

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

$$P_F = P_P K^{TL}$$

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

Assuming that fish productivity near OTEC is similar to that in the upwelling area, the ecological efficiency *K* is 0.2 and the trophic level *TL* is 1.5. *(Otsuka, 2008)*

However, the nutrients brought by deep seawater may be carried away by ocean currents, so this method may be overestimated.

Then assuming that the increased nutrients contribute to only the primary production (ignore the consequent effects on fish productivity), then BC changes can be calculated as

$$BC_{Fertilization} = f_{sea} \frac{P_P}{P_{P_{coastal}}}$$

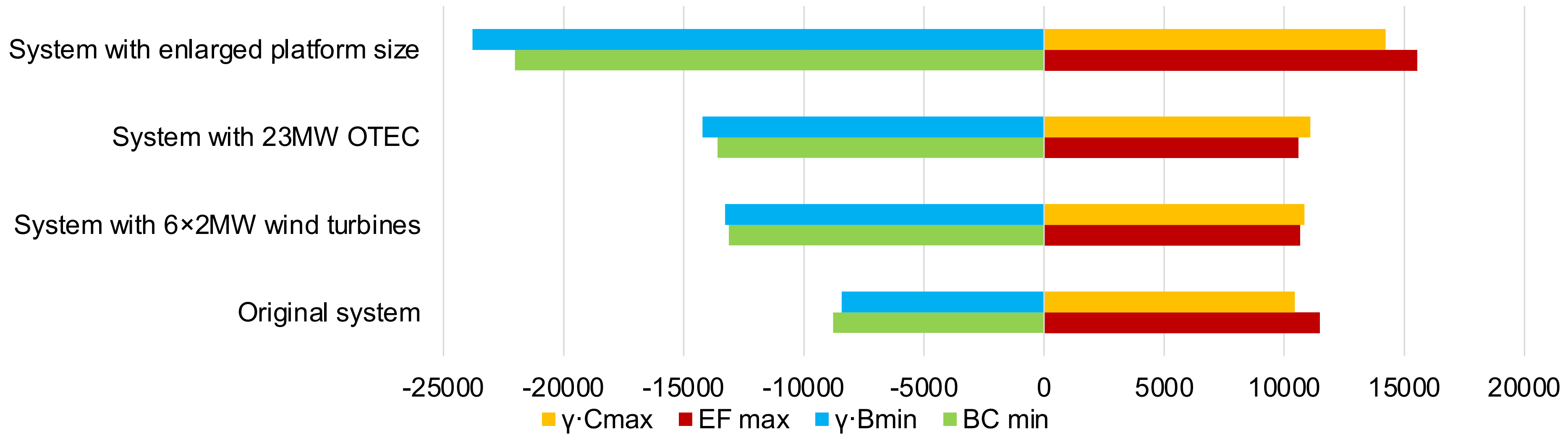
The actual BC value is between these two results.

P_P: The annual primary production P_P (t-C/y)
α_{CN}: The C/N ratio of the phytoplankton, α_{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)
Y_{F0}: The average annual fish production in the productive sea area
$P_{P_{coastal}}$: Primary productivity in the coastal area, $P_{P_{coastal}}$ = 100 (g-C/m^2/year)

4 Assessment Results

Assessment Results

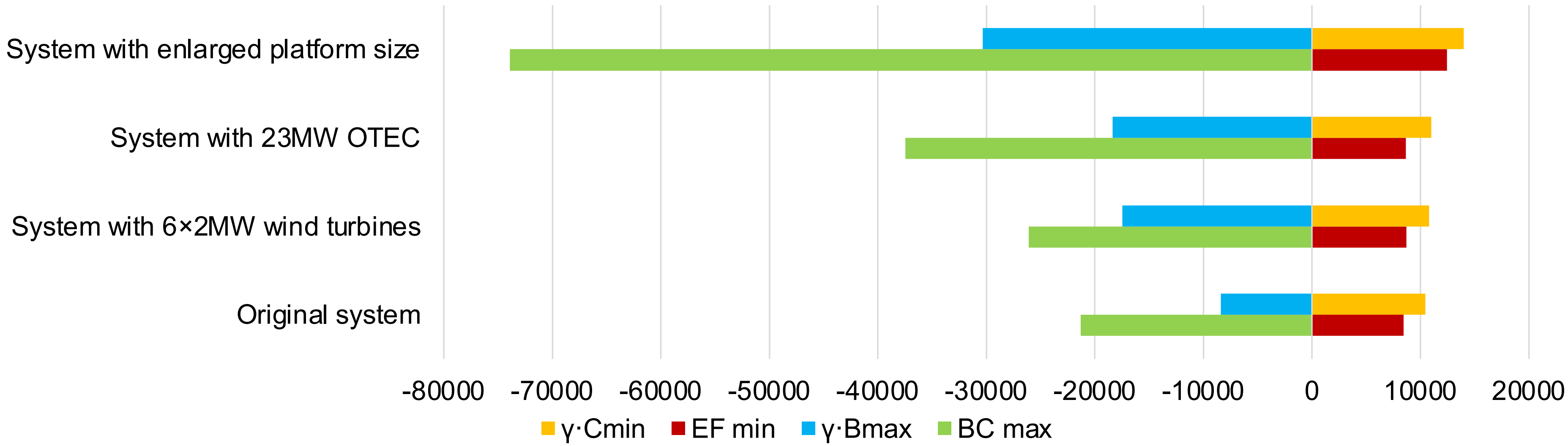
Calculated annual components of worst Triple I



	EF (gha)	*BC* (gha)	Cost (M Yen)	Benefit (M Yen)	III_{light} (gha)	III_{light}^*
Original system	11482	8788	8215	6625	**4713**	**1.27**
System with 6×2MW wind turbines	10645	13129	8531	10458.9	-4786	0.82
System with 23MW OTEC	10590	13582	8731	11187.3	-6112	0.78
System with enlarged platform size	15520	22034	11196	18739.8	-16095	0.65

Assessment Results

Calculated annual components of optimal Triple I

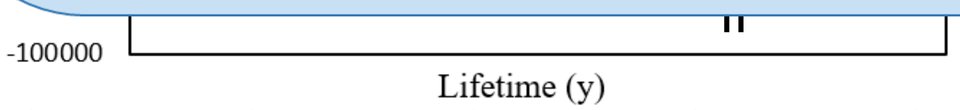


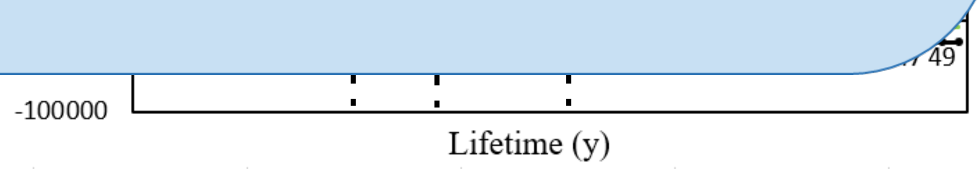
	EF (gha)	*BC* (gha)	Cost (M Yen)	Benefit (M Yen)	III_{light} (gha)	III_{light}^{*}
Original system	8427	21762	8215	6625	-11315	0.63
System with 6×2MW wind turbines	8698	26103	8489	13752.4	-24092	0.45
System with 23MW OTEC	8640	37452	8662	14480.8	-36202	0.35
System with enlarged platform size	12464	73926	11024	23900.8	-77815	0.25

Assessment Results

Lifetime dependence of Triple I

		Environmentally Neutral	Profitable	Sustainable
Original system	Max Min	/ 17 years	/ /	/ 19 years
System with 6×2MW wind turbines	Max Min	37 years 14 years	38 years 27 years	38 years 19 years
System with 23MW OTEC	Max Min	35 years 10 years	36 years 26 years	36 years 15 years
System with enlarged platform size	Max Min	30 years 7 years	25 years 19 years	27 years 10 years





5 Comparison with conventional aquaculture system

Comparison with conventional aquaculture system

Calculated annual composition of Triple I for conventional aquaculture system, which produces the same sea bream production as the multi-purpose system with 23MW OTEC *(Kallitsis, 2020)&(Kitazawa, 2008)*

Term	Source	Estimation/y
Ecological Footprint	**Total (*EF*)**	**51660(gha)**
	Fish aquaculture facility	712 (gha)/n
	Production of feed	48836 (gha)
	Electricity	1112 (gha)
	Packaging	702 (gha)
	Transportation	225 (gha)
	Treatment of aquaculture waste	1950(gha)
Biocapacity	Replacing the same production in fishery	**12769(gha)**
Cost	**Total (*C*)**	**4753(10^6 Yen)**
	Fish aquaculture facility	17144(10^6 Yen)/n
	Transportation	25 (10^6 Yen)
	Feed	3112 (10^6 Yen)
	Electricity	215(10^6 Yen)
	Maintenance	875 (10^6 Yen)
	Labor	200(10^6 Yen)
Benefit	**Total (*B*)**	**13174(10^6 Yen)**

Assessment Analysis

Comparison with conventional aquaculture system

	Multi-purpose system with 23MW OTEC	Conventional aquaculture system
Lifetime (year)	50	50
Production	Fish 6578t/y Hydrogen 1089t/y	Fish 6578t/y
Ecological Footprint (gha)	8640~10590	51660
Biocapacity (gha)	13582~37452	12769
Cost (Million Yen)	8662~8731	4753
Benefit (Million Yen)	11187.3~14480.8	9880.5~13174
III_{light} (gha)	-6112~-36202	28196~32379
III_{light}^{*}	0.35~0.78	1.96~2.28

- Conventional aquaculture system is more profitable (larger B-C), but the multi-purpose system has a significant advantage in environmental impact.
- Because of the high initial investment cost of the multi-purpose system, a long lifetime is required for the advantage to be realized.
- At least 16 years of lifetime in the worst case is required for the multi-purpose system to be better than the conventional aquaculture system, while only 7 years is required in the optimal case.

6 Conclusion

Conclusion

- Improved the system design of the offshore multi-purpose platform.
- Proposed a new calculation method of biocapacity caused by ocean fertilization and environmental impacts other than CO_2 emissions.
- Assessed the sustainability performance of the original and modified systems using the Inclusive Impact Index and confirmed the improved sustainability and economy of the modified systems.
- Compared the offshore multi-purpose system with conventional aquaculture system and demonstrated the advantages of the multi-purpose system in the long lifetime.

Thanks for your attention!