FINANCE MODELING OF A FLOATING OFFSHORE WIND PROJECT IN SOUTH KOREA WITHOUT GOVERNMENT SUBSIDES

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Abstract

The South Korean government is encouraging the active participation of power generation companies in the offshore wind power project by announcing the renewable energy certificates (REC) weighting plan. However, from a long-term perspective, offshore wind power must be able to generate profits without government support to demonstrate its business feasibility and attract the voluntary participation of power generation companies. This is because government support may be subject to change, depending on the internal and external political circumstances of the country. This report calculates the expected costs for a 495 MW floating offshore wind farm in the South Korea's market environment and examine how the feasibility of the project shifts depending on the country's current REC weights. Furthermore, this study intends to determine whether floating offshore wind power can generate profits without the Korean government's support by calculating the expected profit in combination with the green hydrogen project. The net present value (NPV), levelized cost of energy (LCoE) and internal rate of return (IRR) indexes are calculated according to the project's specific particularities, such as power purchase agreement, REC Weighting, distance from shore and sea depth. Based on this, an index-based comparison is revealed and the margin for profitability for such an investment is discussed.

Keywords: floating offshore wind, wind energy, green hydrogen, finance modeling, zero subsidy

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Executive Summary

This study calculated the profitability of floating offshore wind power under various conditions to determine the conditions are necessary for its business feasibility without government support. To this end, first, the NPV, IRR, LCoE, and system marginal price (SMP) + 1 REC (i.e., the revenue consumed by the power producers per 1 MWh of electricity produced from wind power) is compared with a change in the REC weight value under the given project conditions.

Thereafter, the NPV, IRR and LCoE of the floating offshore wind project in combination with a green hydrogen project were calculated in the absence of government support (REC weight "0") when the operating period of the project was divided into 20 and 30 years. In this case, the capacity of the electrolyser was varied according to a change in the curtailment rate. As the curtailment rate increased, the capacity of the polymer electrolyte membrane (PEM) electrolyser and the hydrogen production increased. In contrast, the overall profitability decreased owing to the decrease in the amount of electricity produced through wind power. This could be attributed to the fact that the profitability from wind power was greater than that from hydrogen power generation.

Because the association of floating offshore wind power with hydrogen power generation may not be profitable in the given project parameters, this study predicted the NPV, IRR, and LCoE through changes in capital expenditure (CapEx), operational expenditure (OpEx), and SMP, which are most directly related to the profitability of floating offshore wind power. The calculation results revealed that with a decrease in CapEx and OpEx or an increase in the SMP under all five assumptions (a, b, c, d, and e in *4.3. Comparison of SMP and IRR at different SMP increase rate and CapEx & OpEx reduction rate),* the value of IRR increased. Particularly, under condition e, even when the operating period of the power plant was 20 years, and the SMP increase rate was 10% (i.e., 76.83 USD/MWh), the IRR value became 6.15%. Under the same conditions, when the operating period was 30 years without an increase in the SMP, the IRR value became 7.23%, which is larger than the discount rate of 6.74%.

Furthermore, under the assumptions a-e, this study examined the change in the LCoE with a decrease in the CapEX and OpEx. The results revealed that as the CapEx and OpEx values decreased, the LCoE also decreased. In addition, the LCoE was lower when the operation of the wind power plant was 30 years compared to when it was 20 years, and the reduced difference between the LCoE at 30 and 20 years of operation was insignificant.

Lastly, based on the analysis results, this study discussed the current REC weight policy of the South Korean government, and described what factors should be changed to achieve the profitability of floating offshore wind power without government support.

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Abbreviations

AbEx	Abandonment expenditure
BAU	Business as usual
BOP	Balance of plant
CapEx	Capital expenditure
CGCF	Common grid connection facility
DevEx	Development expenditure
GHG	Greenhouse gas
IRR	Internal rate of return
KEA	Korea energy agency
KEPCO	Korea electric power corporation
KPX	Korea power exchange
LCoE	Levelized cost of energy
LCoH	Levelized cost of hydrogen
MOEF	Ministry of economy and finance
MOF	Ministry of maritime affairs and fisheries
MOTIE	Ministry of trade industry and energy
NDC	Nationally determined contributions
NPV	Net present value
OpEx	Operational expenditure
PEM	Polymer electrolyte membrane
PPA	Power purchase agreement
PRS	Renewable energy portfolio standard
SMP	System marginal price
RE3020	Renewable energy 3020
REC	Renewable energy certificates
SLD	Single line diagram
TJB	Transition joint bay
USD	United states dollar
KRW	Korean won
WACC	Weighted average cost of capital
WTG	Wind turbine generator

1. Introduction

Countries make an effort to reduce the use of fossil fuels and increase the utilization of renewable energies to maintain the global average temperature below 2°C above pre-industrial levels and, ideally, to aim for 1.5°C (UNFCC, 2015). However, under the current policies and economic conditions of most countries, the yield of electricity production from renewable energies is on the rise but still falls short of the global electricity demand (IEA, 2021).

In June 2015, South Korea, in prompt response to the Paris Agreement following the Kyoto Protocol, set its 2030 target of reducing its GHG emissions by 37% from BAU levels (851 million tons) (The Korean government, 2015). In July 2018, it further expanded the scale of its domestic reduction from 25.7% to 32.5%, based on its target of 37% from BAU levels (CNGGC, 2018), by updating the "Basic Roadmap for Achievement of the 2030 National GHG Reduction Goal." Moreover, in December 2019, South Korea modified the nationally determined contributions to clarify its willingness to reduce GHG emissions by 24.4% from 2017 levels and 26.3% from 2018 levels (CNGGC, 2018). Thereafter, in consideration of international trends and domestic conditions, South Korea set the goal of reducing GHG emissions by 35% or more from 2018 levels by 2030 (CNGGC, 2018), announcing the 2030 NDC upgrade plan to the international community in April 2021.

To achieve this aggressive NDC goal, the South Korean government announced a detailed roadmap–the RE3020 Plan–in 2017 to increase the proportion of renewable energies to 20% by 2030, recognizing the need for an expanded supply of renewable energies (MOTIE, 2017). This plan aims to expand renewable energy facilities with a capacity of 48.7 GW by 2030 (the rated capacity for overall renewable energies is 63.8 GW) (MOTIE, 2017), and to concentrate 95% of the rated capacity on solar and wind power generation. The expected proportion of new wind power generation to renewable energy power generation is 16.5 GW (CNGGC, 2018), and if the supply of renewable energies becomes available according to the government's plan, wind power will account for 17.7 GW (CNGGC, 2018) or approximately 28% of the rated capacity for renewable energy power generation facilities in 2030. Furthermore, in July 2020, the government announced the "Offshore Wind Power Development Plan in Win-Win Partnership with the Fishery Industry along with Residents," which outlined the country's aspiration to be one of the world's five largest offshore wind power powerhouses by 2030 (MOF, 2020).

Offshore wind power generation is advantageous in that more energy yield can be expected by installing wind turbines in the sea, where the quality of wind energy resources is superior to that of land (Global Wind Altas, n.d.). In particular, floating offshore wind farm is recognized as a new field of renewable energy worldwide to meet the projected increased in the electricity demand (GWEC, 2022), and the policy support and financial incentives provided by governments around the world are unleashing its great growth potential. However, the biggest challenge for renewable energy generation companies is cost. The installation cost of offshore wind power increases the farther the installation area is from shallow regions near the shore. In addition, foundation structures, power grid connections, and the development of turbines dedicated to offshore wind turbines account for such a high cost (Stehly, T. and Patrick, D., 2021).

Thus, the South Korean government is encouraging the active participation of power generation companies in the offshore wind power project by announcing the REC Weighting Plan (MOTIE, 2017). However, from a long-term perspective, offshore wind power must be able to generate profits without government support to demonstrate its business feasibility and attract the voluntary participation of power generation companies. This is because government support may be subject to change, depending on the internal and external political circumstances of the country (COWI, 2021). Therefore, a*lthough the South Korean government is currently providing the subsidy system of offshore wind, this report aims to identify whether a 495 MW floating offshore wind farm in the country can generate profits in the Korea's market environment without the subsidy and governmental support. An economic analysis will be performed by calculating the NPV, LCoE, and IRR indexes according to the project's specific particularities, such as PPA, REC weighting, distance from shore and sea depth. In addition, this report will examine how the feasibility of the project shifts depending on the capacities of the green hydrogen project. Furthermore, based on these scenarios, the viability of each scenario and the margin for profitability for such an investment will be discussed after carrying out an index-based comparison.*

2. Literature Review

2.1. *Offshore Wind Power in the World*

As of 2020, the total global wind capacity was 742.6 GW, of which 35.1 GW accounted for the proportion of offshore wind power (GWEC, 2021a). In 2021, the total installed wind capacity was 837 GW, which represents an increase of 12.4% from the previous year (GWEC 2022b). The new global wind power installation in 2021 was 93.6 GW, of which 21.1 GW accounted for the proportion of new offshore wind power (GWEC, 2022a). The newly added rated capacity in China is 16.8 GW, accounting for 80% of the total, followed by the UK with 12.3 GW or 11%, and Vietnam with 8.4 GW, or 4% (GWEC 2022b). The total of these three countries amounts to 95%, leading to new addition to the rated capacity. The offshore wind power market is expected to grow significantly in the next 30 years, and the cumulative rated capacity worldwide is projected to reach 228 GW and 1,000 GW in 2030 and 2050, respectively (IRENA, 2020a). These data suggest that the market will grow by an average annual growth rate of 11.5% in the next 30 years (IRENA, 2019a). Offshore wind power is expected to account for approximately 17% of the global cumulative rated capacity (6,044 GW) in 2050 (IRENA, 2019b).

2.2. *Offshore Wind Power in South Korea and Ulsan City*

As of 2020, the domestic wind power generation capacity is 1.64 GW (KWEIA, n.d.). Although the capacity of offshore wind power is 142 MW, and that of offshore wind power in commercial operations is 124 MW (MOTIE, 2021a) local governments and private business operators are actively developing offshore wind power generation projects, such as floating offshore wind power in Shinan, Jeollanam-do, the Southwestern region of Jeollabuk-do, and the Southeastern region of Ulsan. As of August 2021, 43 projects have received licenses and business permits to engage in power generation, amounting to a capacity of approximately 9.6 GW (MOTIE, 2021a). Furthermore, based on South Korea's RE3020, which aims to achieve a 20% proportion of renewable energy generation by 2030, as well as the 3rd Energy Masterplan prescribing a 30%–35% proportion by 2040, this industry will continue to expand in the future (MOTIE, 2019b).

Ulsan, which faces the East Sea to the east, is a representative industrial city in South Korea. The East Sea is characterized by a wide continental shelf with a water depth of 100 to 200 m, exposed to the wind with an average annual wind speed of 8 m/s or more (Ulsan Metropolitan City, 2021b). Moreover, due to its geographical conditions, the city is home to shipbuilding and offshore plant companies in addition to substantial human resources. Because the offshore wind power sector can converge with shipbuilding and marine technology, Ulsan is promoting its administrative target of launching the first floating offshore wind power generation complex in South Korea. By 2030, the world's largest floating offshore wind farm with a capacity of 6 GW will be built offshore of Ulsan (Ulsan Metropolitan City, 2021a).

2.3. South Korea's Renewable Energy Policies – Offshore Wind Energy

2.3.1. Korea's RE3020

In December 2017, the MOTIE announced the Renewable Energy 3020 Plan (draft) through the Second Renewable Energy Policy Council. In this regard, 48.7 GW of new renewable energy generation facilities will be supplied between 2018 and 2030 to increase the proportion of renewable energy generation to 20% by 2030 (KEA, 2018). According to this plan, 95% or more of new renewable energy generation facilities will be mainly focused on solar and wind-centered energy, and expansion of the supply of renewable energies will promote shared growth in the energy industry (KEA, 2018). Furthermore, the MOTIE aims to promote large-scale projects of five and 23.8 GW in the first and second phases, respectively, by utilizing idle nuclear and coal power plant sites (MOTIE, 2019b).

2.3.2. The 3rd Energy Masterplan

The 3rd Energy Masterplan consists of five key promotional tasks for "sustainable growth and improvement of the quality of life of people through energy conversion." Regarding the matters related to new and renewable energies in this plan, the proportion of renewable energy generation will be raised to 30%–35% by 2040 (MOTIE, 2019b), and the target proportion of their power generation will be specified through "The Basic Plan for Power Supply and Demand" to be established in the future. Moreover, this plan aims to facilitate the transition to a clean and safe energy mix through gradual and drastic reductions in nuclear and coal power generation.

2.3.3. The 5th Basic Plan for New and Renewable Energy and The 9th Basic Plan for Power Supply and Demand

The Basic Plan for New and Renewable Energy is revised every five years for a period of ten years or more per Article 5 of the "Act on The Promotion of the Development, Use and Diffusion of New and Renewable Energy". This Basic plan aims to present mid- to long-term goals and implementation plans in the field of new and renewable energies in conjunction with the "Energy Masterplan," the umbrella plan in the energy sector. The main feature of the 5th Basic Plan for New and Renewable Energy is to secure consistency in the long-term energy sector plan in line with the period and goals of the 9th Basic Plan for Power Supply and Demand. Thus, this 5th Basic Plan is set for the same 2020–2034 period, as well as the target proportion of new and renewable energy generation in 2034 at 25.8% (MOTIE, 2020), as in the 9th Basic Plan for Power Supply and Demand. The 9th Basic Plan for Power Supply and Demand aims to secure

77.8 GW of renewable energy installation capacity by 2034 through alignment with RE3020 (MOTIE, 2020a), the Hydrogen Economy Roadmap, the 3rd Energy Masterplan, the revised New and Renewable Energy Act, and the Green New Deal plan. In this plan, the shares of solar and wind power are 45.6 and 24.9 GW, respectively, accounting for 91% of the total installation capacity of renewable energies in 2034 (MOTIE, 2020a). Figure 1 shows the government's renewable energy development plan in South Korea by 2035 based on the 9th Basic Plan for Power Supply and Demand.

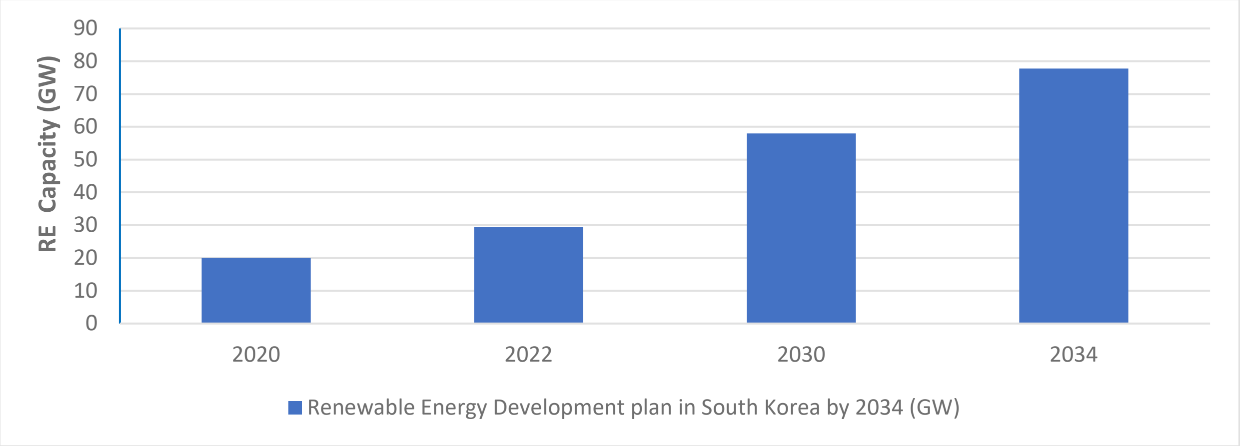

Figure 1. Renewable energy development plan in South Korea by 2034 (MOTIE, 2020a)

2.3.4. The Korean New Deal – Green New Deal

The Korean New Deal is a national development strategy designed to overcome the crisis after COVID-19 in the face of the worst economic recession and shocks to labor demand due to the pandemic. The Green New Deal, a promotional plan encompassed in the Korean New Deal, created a foundation to support the implementation of the countries' NDC to the Paris Agreement and improved related systems. Details of the Green New Deal are as follows:

- Increase domestic renewable energy generation capacity to 12.7, 26.3, and 42.7 GW in 2020, 2022, and 2025, respectively (MOEF, 2020).

- Raise the RPS ratio ceiling from 10% to 25% through the revision of the Act on the Promotion of the Development, Use, and Diffusion of New and Renewable Energy in 2021(MOEF, 2021).
- Create 120,000 jobs in prospect by constructing the Shinan offshore wind farm with a capacity of 8.2 GW by 2030 (MOEF, 2021).
- Create 210,000 related jobs in prospect through the construction of the Ulsan floating offshore wind farm with a capacity of 6 GW and the production of green hydrogen by 2030 (MOEF, 2021).
- Attract large-scale private investment announcements of investment plans for a total of KRW 43 trillion in the hydrogen sector by 2030 (March 2021), and a total of KRW 36 trillion in floating offshore wind power (May 2021) (MOEF, 2021).

2.3.5. Offshore Wind Power Development Plan in Win-Win Partnership with the Fishery Industry along with Residents

Currently, in South Korea, wind power developers are required to proceed independently to locate sites and gain residents' acceptance for building power plants, complaining of difficulties due to insufficient government-level support. Furthermore, the fisheries industry has been continuously raising concerns over the reduction of fishing zones due to the creation of offshore wind farms and negligence in consulting with actual users of the sea area. Thus, the South Korean government collected opinions from related industries, based on which they announced the “Win–Win Plan for Developing Offshore Wind Power with Residents and the Fisheries Industry.” The main element of the plan was the completion of a 12 GW offshore wind power generation facility by 2030 (MOTIE, 2020b), with a proposed support scheme and various enhancement measures for acceptance, environmental quality, and industrial competitiveness, to facilitate South Korea's emergence as one of the world's top five offshore wind power generation countries. Details of the development plan are as follows.

- Support scheme: promotion of government-led search for suitable sites and introduction of a one-stop shop (MOTIE, 2021a).
- Acceptance and environmental quality: construction of an eco-friendly offshore wind power complex desired by residents by expanding the generation profit-sharing model with residents and improving the environmental quality in the life cycle (MOTIE, 2021a).
- Provision of enhancement measures for industrial competitiveness: promotion of the mutual growth of the offshore wind power market and industries through preemptive investment in power grid systems, development of large-capacity turbines, and establishment of related infrastructure, such as support ports (MOTIE, 2021a).

2.4. South Korea's Renewable Energy Policies – Green Hydrogen

The South Korean government selected the hydrogen economy as one of three strategic investment areas in August 2018 and announced the establishment of the Hydrogen Economy Roadmap in 2019. This roadmap recognizes the hydrogen economy as a new growth engine for innovative growth and a driving force for an eco-friendly energy supply. In addition, it contains macroscopic policy directions, goals, and promotional strategies for revitalizing the hydrogen economy by 2040. Regarding offshore wind power, the government plans to secure water electrolysis technology linked to MW-level renewable energy plants by 2022 and to mass-produce green hydrogen by linking it with large-scale solar and wind power generation. As seen in Figure 2 below, the government aims to increase hydrogen production from 130,000 tons in 2018 to 5.26 million tons in 2040, providing a stable supply of a substantial amount of green hydrogen to induce a drop in the hydrogen price below 3,000 KRW/kg (MOTIE, 2019a).

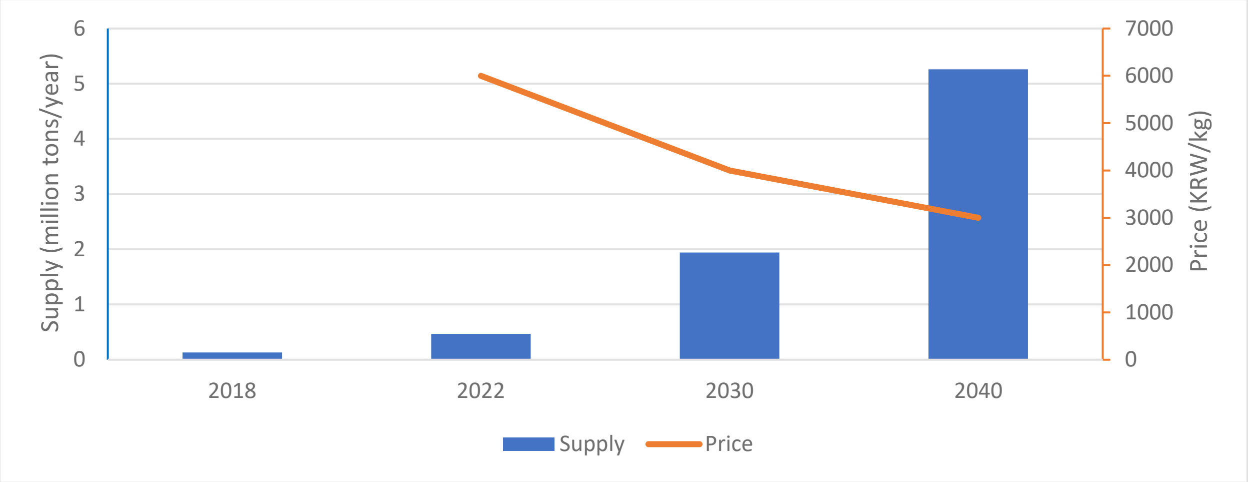

Figure 2. Green hydrogen supply and price plan in South Korea by 2040 (MOTIE, 2019a)

2.5. A Way to Zero-subsidy

The governments of major countries have subsidized the new renewable energy industry to foster its development. Beginning in 2015, many countries started introducing the auction system, as the yield of renewable energy production rapidly increases, and the financial burden becomes intolerable (IRENA, 2015). In response to the changing policy environment, the wind turbine industry is moving in the direction of reducing development costs and enhancing power generation efficiency by scaling up wind turbines (Shields, M., Beiter, P., Nunemaker, J., Cooperman, A. and Duffy, P., 2021).

This trend of increasing turbine capacity will continue. The industry currently plans to develop a large turbine with a capacity of 15–17 MW by 2025, and the development of an offshore wind turbine with a capacity of 20 MW is further expected (GWEC, 2022b). The CapEx per MW for these large-scale turbines will increase, while the LCoE will decrease, as the yield of power generation increases due to high power generation efficiency and the cost required for the foundation structure or its installation decreases. The OpEx will further decrease due to improved reliability and ease of maintenance, resulting in a reduction in LCoE (COWI, 2021).

2.6. Project Cost Forecast towards 2050

2.6.1. Offshore Wind Project Cost – LCoE

The average LCoE of global offshore wind power will range from \$0.05/kWh to \$0.09/kWh in 2030, and from \$0.03/kWh to \$0.07/kWh in 2050 (IRENA, 2019a). As the LCoE reaches these levels, offshore wind power will be able to compete on an equal footing with power generation from fossil fuels without significant financial support, considering that the average LCoE of global fossil fuels' price range is from \$0.05/kWh to \$0.18/kWh (IRENA, n.d.).

2.6.2. Green Hydrogen Project Cost – LCoH

The two main drivers that have a direct impact on the reduction of total LCoH are the LCoE and the CapEx for PEM electrolyser. In the case of a floating offshore wind project in combination with the green hydrogen project, the LCOH costs £9.12/kg H2 in 2020. It is expected that LCoH decrease to £2.89/kg H2 by 2030. It is because LCoE drops by £5.23/kg H2 which accounts for nearly 58% of the total LCoH in 2020. It is also expected that LCoE reduces by 88% by 2040, and 68% by 2050 leading to an LCoH costs £2.14/kg H2 by 2040 and £1.78/kg H223 by 2040 (OWIC & ORE, 2020).

3. Methods

3.1. Project Information and Assumptions

3.1.1. Single Line Diagram

Figure 3 is the basic SLD for the project in the paper. As it is indicated, the electricity produced by the wind turbine generators are connected with 66 kV AC offshore cables to the offshore substation where 66 kV / 220 kV AC transformers are placed. The electricity is then transferred to the national grid through the transition joint bay, onshore substation, and common grid connection facility. The main purpose of TJB is to connect the offshore cables with the onshore cables. The onshore substation serves as an electrical interface point of the wind farm to the national grid system. It includes different electrical equipment such as 220 kV / 345 kV AC main transformers, Gas insulated switchgears, reactors, etc. Finally, CGCF is a changing station where different developers can connect their wind farm systems before sending the produced power to the national grid system.

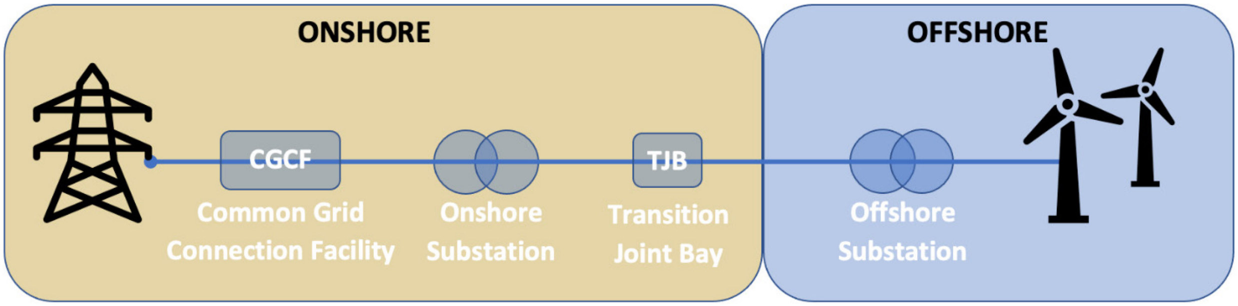

Figure 3. Basic Single Line Diagram for the Floating Offshore Wind Project

3.1.2. Project Parameters

There are no large-scale floating offshore wind farms in operation in South Korea. Thus, assuming project information, this study utilized the information available in the South Korean market, while applying some parameters obtained from overseas floating offshore wind farms and research results to the South Korean market. *Table 1* indicates the assumed project parameters for the study in the paper.

The capacity of the offshore wind farm was selected accordingly because the publicly available capacity for a potential supplier to apply for the selection of a competitive bidder for a fixed price contract of wind power is 550,000 kW (KEA, 2022b), and because the capacity of a bank of 345 kV, which is mainly used in South Korea, is 500 MVA. Currently, Vestas' V235 model has a 15-MW (Vestas, n.d.) WTG for floating offshore wind farm, and the total capacity of the floating offshore wind farm when the above 33 units of models are used becomes 495 MW.

Linkage distance refers to the straight-line distance between the coastline and the central position of the wind generator closest to the coastline (MOTIE, 2021b). The water depth refers to the depth of the basic level surface to sea level of the wind farm where the floating WTG is installed (MOTIE, 2021b). However, when several WTGs are installed in one offshore wind power plant, a weight is applied to the average depth of the WTGs (MOTIE, 2021b). For the location of the floating offshore wind farm, the linkage distance and water depth were assumed by referring to the locations of the actual projects that are currently under development in the East Sea near Ulsan.

The CapEx cost was calculated under the subcategories of electrical cost and civil cost, and the price suitable for the South Korean market was calculated by referring to the 2022 standard unit price for the construction sector budget provided by the KEPCO. Additionally, the WTG price, OpEx, DevEx, and AbEx were calculated based on the information obtained from overseas floating offshore wind power plants, and the reports from overseas consulting companies. The Net Capacity Factor includes the gross capacity factor, wake loss, line loss, and availability of the plant. This study selected the capacity of the hydrogen electrolyser and the wind power generation according to the curtailment rate, and further details are provided in *4. Results and Analysis*.

The information provided by the Korean government was used for the issues related to taxation and financing. The cost for the green hydrogen project was calculated based on the hydrogen-related reports published by IRENA in the last three years. This study assumed that the PEM electrolyser was installed at sea. Moreover, because the produced hydrogen was assumed to be stored and transported domestically or abroad via a vessel, the transport price provided in *Table 1* below refers to the price of the hydrogen stored as ammonia and transported via a vessel. In addition, under the assumption that the electrolyser can be operated for an average of 8 hours a day, the capacity factor of the PEM electrolyser becomes approximately 33%.

Category	**Value**	**Unit**	**Reference**
1 USD to KRW	1201.4	KRW	Bloomberg, n.d.
Base Year	2025	year	Project Parameters
Wind Farm Capacity	495	MW	Project Parameters
Number of WTG	33	EA	Project Parameters
WTG Capacity	15	MW	Project Parameters
Net Capacity Factor	39.53	%	Project Parameters
Linkage Distance	70	km	Project Parameters
Water Depth	150	m	Project Parameters
CapEx-Wind	5,050 million	KRW/MW	KEPCO, 2022
OpEx-Wind	81 million	KRW/MWh-year	NREL, 2020
DevEx-Wind	80,000 million	KRW	Project Parameters
AbEx-Wind	72.5 million	KRW/WTG	Project Parameters
CapEx-PEM Electrolyser	700	USD/kW	IRENA, 2018
OpEx-PEM Electrolyser	14	USD/kW	IRENA, 2018
System Lifetime	20	Years	IRENA, 2018
Lifetime Stack	80,000	Hours	IRENA, 2018
CapEx-Stack Replacement	400	USD/kW	IRENA, 2018
PEM Efficiency	0.058	MWh/kg of H_2	IRENA, 2018
Running Hours	8	Hours/day	Project Parameters
Capacity Factor	33	%	Project Parameters

Hydrogen Price	6000	KRW	MOTIE, 2019a
Transport (Ammonia) by ship	1800	KRW/kg of H_2	IRENA, 2019c
Corporate Tax rate	25	%	NTS, 2022
Depreciation Schedule: Straight-line 20-year	5	%/year	Supreme Court of Korea, 2022
Equity	30	%	Project Parameters
Debt	70	%	Project Parameters
Pre-tax debt rate	6	%	Project Parameters
Dept term	15 years	Years	Project Parameters
Inflation	2.3	%	The World Bank, 2021
Equity rate	7	%	Project Parameters
WACC	6.74	%	Project Parameters

Table 1. Project Parameters

3.2. NPV

The NPV provides a comparative way to evaluate capital or financial products based on their current cash flows and is given by the formula (Equation (1)) (Ucal, M. and Xydis, G., 2020):

$$NPV = \frac{R_t}{(1+r)^t} \tag{1}$$

where:
R_t = net cash flow (inflow-outflows) in year t
r = discount rate
t = year of the cash flow

3.3. *IRR*

The IRR index is another way to assess the viability of future investments. The scope is to identify the rate by which the investor will get their capital back and it is calculated via the formula (Equation (2)):

$$NPV = \sum_{t-1}^{t} \frac{C_t}{(1+r)^t} - C_o \tag{2}$$

where:
C_t = Net Cash inflow in year t

C_o = total capital cost
r = Internal rate of return

3.4. *LCoE*

The LCoE is calculated based on Equation below (Equation (3)) (Lai, C.S. and McCulloch, M.D., 2017):

$$LCoE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{3}$$

where:
I_t = Investment expenditures in year t
M_t = Operations and Maintenance expenditures in year t
E_t = Electricity generation in year t
r = Discount rate
n = Life of the wind turbine systems

3.5. *PPA*

The PPA is a system, in which a power producer of renewable energies selected through competitive bidding concludes a contract to supply RECs at a fixed price for 20 years with a potential supplier of RPS. While participating in the fixed-price bidding, the bidding price must be the sum of the SMP and REC costs. Thus, the revenue of a power plant can be said to be the sum of the electricity sales revenue and the REC sales revenue (KEA, 2022a).

The PPA is calculated as below (Equation (4)) (KEA, 2022b):

$$PPA = SMP + 1REC \cdot (REC\ Weight) \tag{4}$$

3.6. *REC*

The REC is a certificate that verifies that a potential supplier has produced and supplied by utilizing new renewable energy facilities, in which the submission of 1 REC is considered to be an implementation performance of 1 MWh. The amount of REC issuance is calculated using

Equation (5) (KEA, 2022b), and the REC weight is largely determined by the energy source, installation type, and capacity. *Table 2* indicates the applicable Basic REC weights to offshore wind only. The method for calculating compound weights will be discussed in detail in *3.8. REC Weight Calculation for Offshore Wind.*

REC Weight	Criterion
2.0	Basic Weight for Coastal area
2.5	Basic Weight

Table 2. Basic REC Weighting Schemes for Offshore Wind (MOTIE, 2021b)

The REC is calculated as below (Equation (5)). If a monthly SMP exceeds a fixed price, REC price is applied to '0' (KEA, 2022b).:

$$REC = (Fixed\ Price + Monthly\ SMP)/(REC\ Weight) \tag{5}$$

3.7. Fixed Price

The Fixed Price is calculated as below (Equation (6)) (KEA, 2022b):

$$Fixed\ Price = (Base\ SMP + (Bidding\ Price - Base\ SMP) \cdot (REC\ Weight) \tag{6}$$

3.8. REC Weight Calculation for Offshore Wind

3.8.1. REC Weight

REC Weight is calculated based on Equation below (Equation (7)) (MOTIE, 2021b):

$$REC\ Weight = Weight_{Distance} + Weight_{Depth} - Weight_{B} \tag{7}$$

where:
$Weight_B$ = Basic REC Weight
$Weight_{Distance}$ = REC Weight according to grid connection distance
$Weight_{Depth}$ = REC Weight according to depth of water

3.8.2. *Weight*$_{Distance}$

Weight$_{\text{Distance}}$ is calculated based on Equations below:

Distance to Grid	**Weight$_{\text{Distance}}$**
≤ 5 km	$Weight_B$
> 5 km and ≤ 10 km	$\frac{(5\ X\ Weight_B) + [(Distance - 5)\ X\ (Weight_B + 0.4)]}{Distance}$
>10 km and ≤ 15 km	$\frac{(5\ X\ Weight_B) + [5\ X\ (Weight_B + 0.4)] + [(Distance - 10)\ X\ (Weight_B + 0.8)]}{Distance}$
> 15 km	$\frac{(5\ X\ Weight_B) + [5\ X\ (Weight_B + 0.4)] + [5\ X\ (Weight_B + 0.8)] + [(Distance - 15)\ X\ (Weight_B + 1.2)]}{Distance}$

Table 3. REC Weights according to the distance to grid (MOTIE, 2021b)

3.8.3. *Weight*$_{Depth}$

Weight$_{\text{Depth}}$ is calculated based on Equations below:

Water Depth	**Weight$_{\text{Depth}}$**
≤ 20 m	$Weight_B$
> 20 m and ≤ 25 m	$\frac{(5\ X\ Weight_B) + [(Depth - 20)\ X\ (Weight_B + 0.4)]}{Distance - 15}$
> 25 m and ≤ 30 m	$\frac{(5\ X\ Weight_B) + [5\ X\ (Weight_B + 0.4)] + [(Depth - 25)\ X\ (Weight_B + 0.8)]}{Distance - 15}$
> 30 m	$\frac{(5\ X\ Weight_B) + [5\ X\ (Weight_B + 0.4)] + [5\ X\ (Weight_B + 0.8)] + [(Distance - 30)\ X\ (Weight_B + 1.2)]}{Distance - 15}$

Table 4. REC Weights according to depth of water (MOTIE, 2021b)

3.9. *Maximum SMP + 1 REC Price*

Type	**Land**	**Jeju Island**
Maximum Price (KRW/MWh)	169,500	172,890

Table 5. Maximum SMP+1 REC Price in Korea (KEA, 2022b)

3.10. *Base SMP*

Type	**Land**	**Jeju Island**
Base SMP (KRW/MWh)	85,900	129,780

Table 6. Base SMP in Korea (KEA, 2022b)

4. Results and Analysis

4.1. Comparison of SMP + 1 REC, LCoE and IRR at different REC Weights

According to the formula for calculating the compound weight of the offshore wind power linkage distance and water depth proposed by the Korean government as at September 2022, the maximum linkage distance standard and the maximum water depth were designated as "more than 15 km," and "more than 30 m," respectively. However, because the limit of the maximum compound weight value is not specified, the total offshore wind power REC weight increased as the length of the linkage increased, and the water depth increased. Thus, this study calculated a REC weight of 4.6 based on a linkage distance of 70 km and a water depth of 150 m, as well as a REC weight of 3.7 based on a linkage distance of 15 km and a water depth of 30 m, according to the project assumptions. Additionally, this study calculated the SMP1 + REC price, LCoE, and IRR depending on the varied REC weight by reducing the REC weight from 3.7 to 0.5 at a certain rate. Furthermore, when there was no REC weight, the SMP1 + REC price, LCoE, and IRR were calculated by dividing the operating period of the wind farms into 20 and 30 years.

As shown in *Figure 4*, when a REC weight of 4.6 is given, the SMP + 1 REC was USD 397.46, which is approximately 5.7 times higher than the monthly SMP (USD 69.84) with an estimated IRR of 27.45%. As the REC weight decreased, the SMP + 1 REC and IRR decreased. However, because the IRR value with a REC weight of 0.9 is 7.12%, power producers can make profits from the business.

When the REC weight was not applied, the SMP + 1 REC decreased from 107.13 to 70.39 USD/MWh, whereas the IRR decreased significantly from 3.92 to -1.42%. Despite the change in the REC weight, there was no change in the LCoE value. However, when the operating period of the wind power plant was increased from 20 to 30 years, the LCoE decreased from 129.1 to 114.67 USD/MWh, and the IRR slightly increased from -1.42 to 2.24%, which is insufficient for power producers to achieve the expected profit.

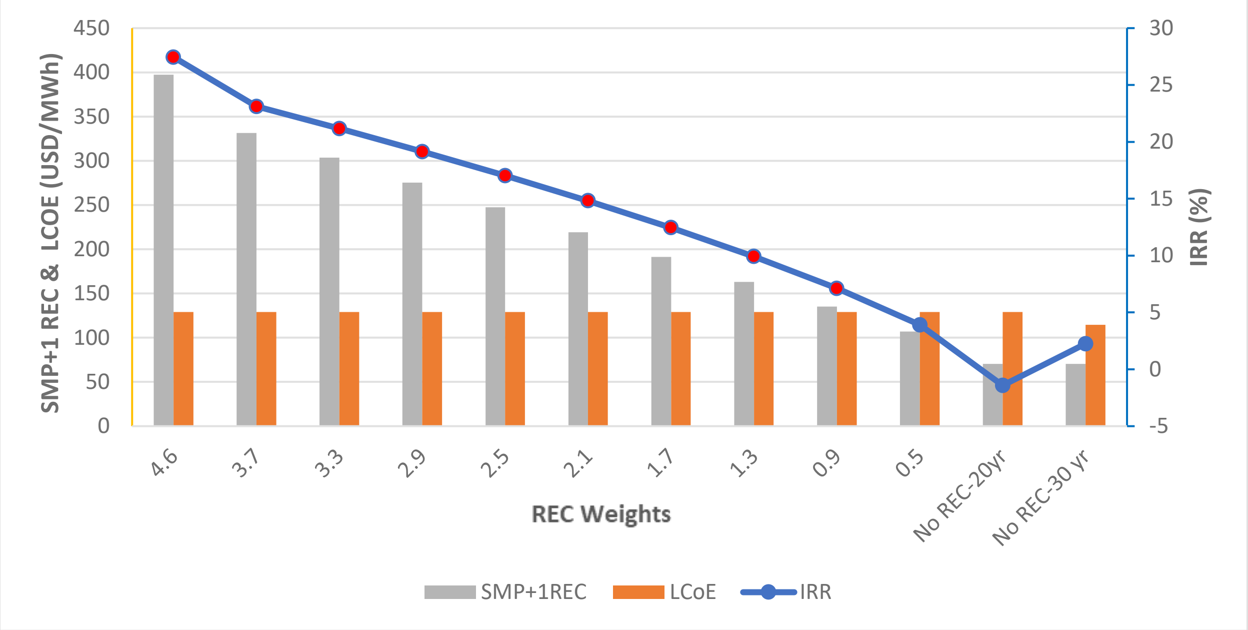

Figure 4. SMP+1 REC, LCoE and IRR at different REC Weights

4.2. Comparison of LCoE, Curtailment rate and IRR at different PEM Electrolyser capacities in 20 years and 30 years operation.

Would the utilization of the electricity wasted owing to curtailment of the offshore wind plant increase the overall profitability if the electricity is used to produce hydrogen through the PEM electrolyser? *Figure 5* and *Figure 6* show the changes in the LCoE and IRR of the floating offshore wind farms according to the capacity of the PEM electrolyser when the operating period of the power plant was 20 and 30 years. The capacity of the PEM electrolyser varies depending on the curtailment rate of offshore wind power farms. In this case, as the curtailment rate increased, the amount of electricity generated through offshore wind power decreased, and the amount of hydrogen produced through the electrolyser increased. As shown in *Figure 5*, when the curtailment rate was increased from 2 to 51% and the operating period of the power plant is 20 years, the capacity of the PEM electrolyser increased from 4 to 100 MW. Additionally, at a curtailment rate of 2%, the annual electricity output of offshore wind power generation was 1,679,785 MWh, whereas with an increase in the curtailment rate to 51%, the output reduced to 839, 982 MWh which decreased in the same ratio as the curtailment rate. Moreover, as the hydrogen production increased, the LCoE continuously increased (129.57 to 184.72 USD/MWh), whereas the IRR exhibited a decreasing trend (-1.59 to -5.89%).

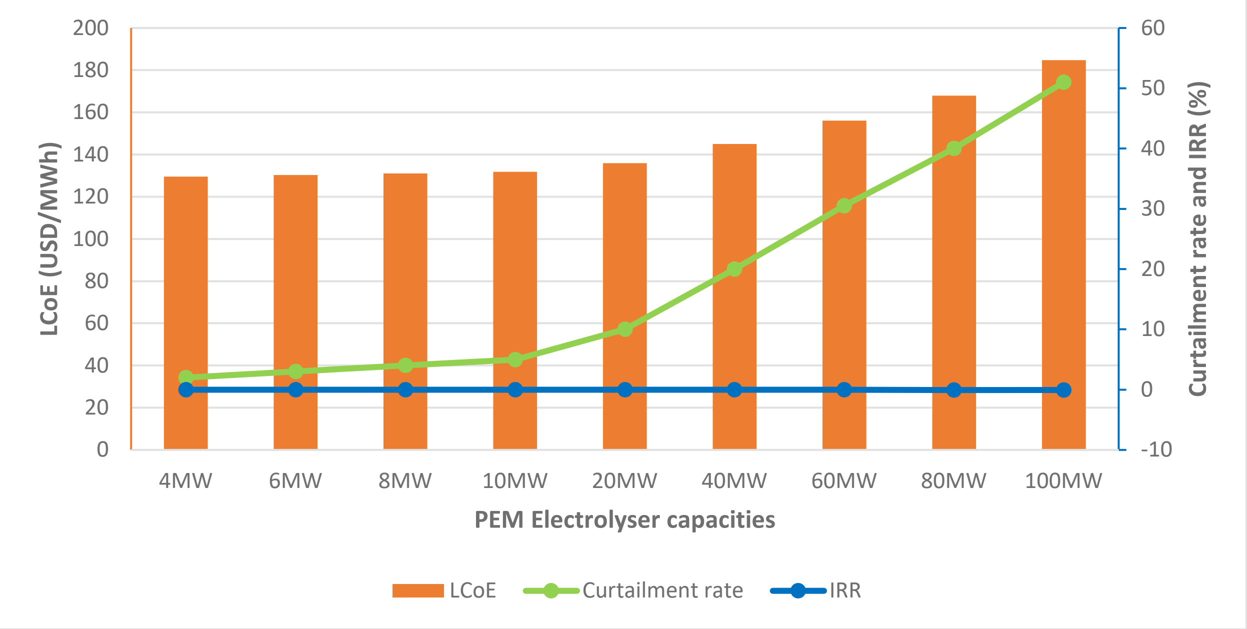

Figure 5. LCoE, Curtailment rate and IRR at different PEM Electrolyser capacities - 20 years of operation

A similar trend was also observed when the operating period of the offshore wind power plant was assumed to be 30 years. As the curtailment rate and hydrogen production increased, the IRR decreased and the LCoE increased. At a curtailment rate of 2%, the IRR was 2.11%, but shifts to a negative value (-0.42%) with an increase in the curtailment rate to 40%. In addition, with an increase in hydrogen production, the LCoE increased from 115.10 USD/MWh. This value is higher than the LCoE of 114.67 USD/MWh when operating offshore wind power for 30 years without government support.

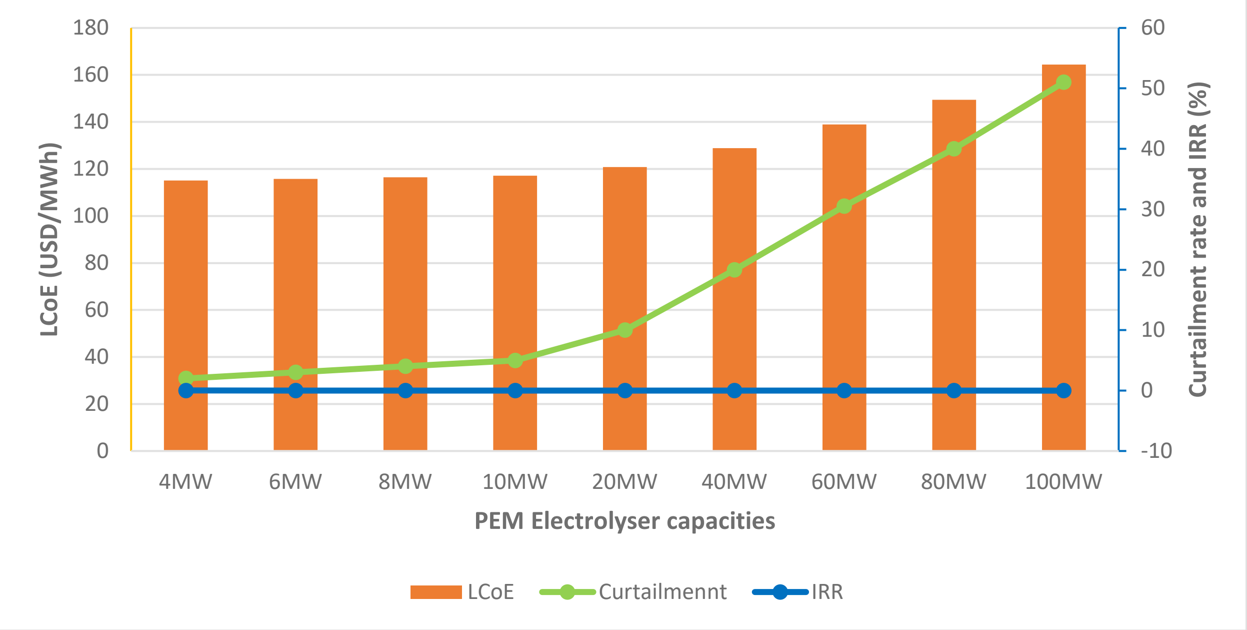

Figure 6. LCoE, Curtailment rate and IRR at different PEM Electrolyser capacities - 30 years of operation

According to the data on the annual curtailment of wind power generation in Jeju Island, a curtailment of 3.36% occurred in the first half of 2020 (KPX, 2020). The frequency of curtailment will increase as the ratio of electricity obtained from renewable energy increases. Thus, the annual power generation, hydrogen production, and LCoH at curtailment rates of 2 and 10% were compared. When the curtailment rate of the wind farm is approximately 2%, a 4-MW PEM electrolyser can be installed. Under this condition, approximately 197,019 kg H_2 of hydrogen per year was produced while a production of annual electricity by wind power generation was 1,679,785 MWh. When the curtailment rate was approximately 10%, a PEM electrolyser of 20 MW can be installed. Accordingly, the annual hydrogen produced under this condition amounts to approximately 985,095 kg H_2 while a production of annual electricity by wind power generation was 1,542,659 MWh. When 4-MW and 20-MW electrolysers are installed, the LCoH at 20 and 30 years of operation is 3.17 and 2.62 USD/kg H_2, respectively, indicating that there was no significant difference in the LCoH under both conditions. If a 100-MW electrolyser is installed, the LCoH at 20 and 30 years of operation will be 3.14 and 2.60 USD/kg H_2, respectively, which is not significantly different from those under 4-MW and 20-MW conditions. This could be attributed to the fact that the capacity of the green hydrogen project is relatively smaller than that of the floating wind power plant. In addition, the low price of LCoH could be attributed to the fact that the cost of electricity to produce hydrogen is "0."

4.3. Comparison of SMP and IRR at different SMP increase rate and CapEx & OpEx reduction rate

The factors most directly related to the profitability of floating offshore wind power are the CapEx and OpEx costs, and SMP. To achieve profitability of the business only with floating offshore wind power generation without government support, it is necessary to examine the trends of the SMP, NPV, IRR and LCoE with a change in the two aforementioned factors. Thus, the following conditions were created.

a. When CapEx decreased by 0%, the change in IRR as SMP increased when the operation period of the wind power plants was 20 and 30 years, respectively.

b. When CapEx decreased by 10%, the change in IRR as SMP increased when the operation period of the wind power plants was 20 and 30 years, respectively.

c. When CapEx decreased by 20%, the change in IRR as SMP increased when the operation period of the wind power plants was 20 and 30 years, respectively.

d. When CapEx decreased by 30%, the change in IRR as SMP increased when the operation period of the wind power plants was 20 and 30 years, respectively.

e. When CapEx decreased by 40%, the change in IRR as SMP increased when the operation period of the wind power plants was 20 and 30 years, respectively.

Table 7 and *Table 8* indicates the results of the changes in IRR at different CapEx and OpEx reduction rate, and SMP increase rate when the operating period of the project was divided into 20 and 30 years, respectively.

20 years of operation	**CapEx & OpEx reduction rate**					
		0%	**10%**	**20%**	**30%**	**40%**
SMP increase rate	**0%**	-1.42	-0.15	1.27	2.91	4.85
	3%	-1.05	0.21	1.65	3.30	5.25
	5%	-0.82	0.46	1.89	3.55	5.51
	7%	-0.58	0.69	2.13	3.80	5.77
▒ : *Close to the discount rate*	**10%**	-0.24	1.04	2.49	4.16	6.15

Table 7. The changes in IRR at different CapEx & OpEx reduction rate and SMP increase rate - 20 years of operation

30 years of operation	**CapEx & OpEx reduction rate**					
		0%	**10%**	**20%**	**30%**	**40%**
SMP increase rate	**0%**	2.24	3.23	4.36	5.67	7.23
	3%	2.52	3.52	4.65	5.97	7.56
	5%	2.71	3.71	4.85	6.18	7.78
	7%	2.89	3.90	5.04	6.38	7.99
	10%	3.16	4.17	5.33	6.68	8.30
	20%	4.02	5.05	6.24	7.63	9.33
	30%	4.83	5.88	7.10	8.55	10.31
	40%	5.59	6.68	7.93	9.42	11.25
▒ : *Close to the discount rate*	**50%**	6.32	7.43	8.73	10.27	12.17

Table 8. The changes in IRR at different CapEx & OpEx reduction rate and SMP increase rate - 30 years of operation

As shown in the tables, when CapEx decreased or SMP increased in all assumptions, the value of IRR further increased. Under condition a, if the SMP becomes 104.77 USD/MWh (i.e., a 50% increase) when the wind power plant is operated for 30 years, the IRR becomes 6.32%, which is slightly below the expected discount rate (6.74%). Even under conditions b, c, and d, the IRR was never close to the expected discount rate for the 20-year operating period even with either an decrease in the CapEx or an increase in the SMP or both: Under condition b with an operating period of 30 years, at an SMP increase rate of 40% (97.78 USD/MWh), the IRR was 6.67%; under condition c, at an SMP increase rate of 20% (83.81 USD/MWh), the IRR was 6.23%; and under condition d, at an SMP increase rate of 7% (74.73 USD/MWh), the IRR was 6.37%, which is close to the discount rate. Under condition e with a plant operating period of 20 years and SMP increase rate of 10% (or the SMP is 76.83 USD/MWh), the IRR becomes 6.15%. Under the same conditions, when the operating period was 30 years, the IRR was 7.23%, which is larger than the discount rate, regardless of the increase in SMP.

4.4. *Comparison of LCoE at different CapEx & OpEx reduction rate*

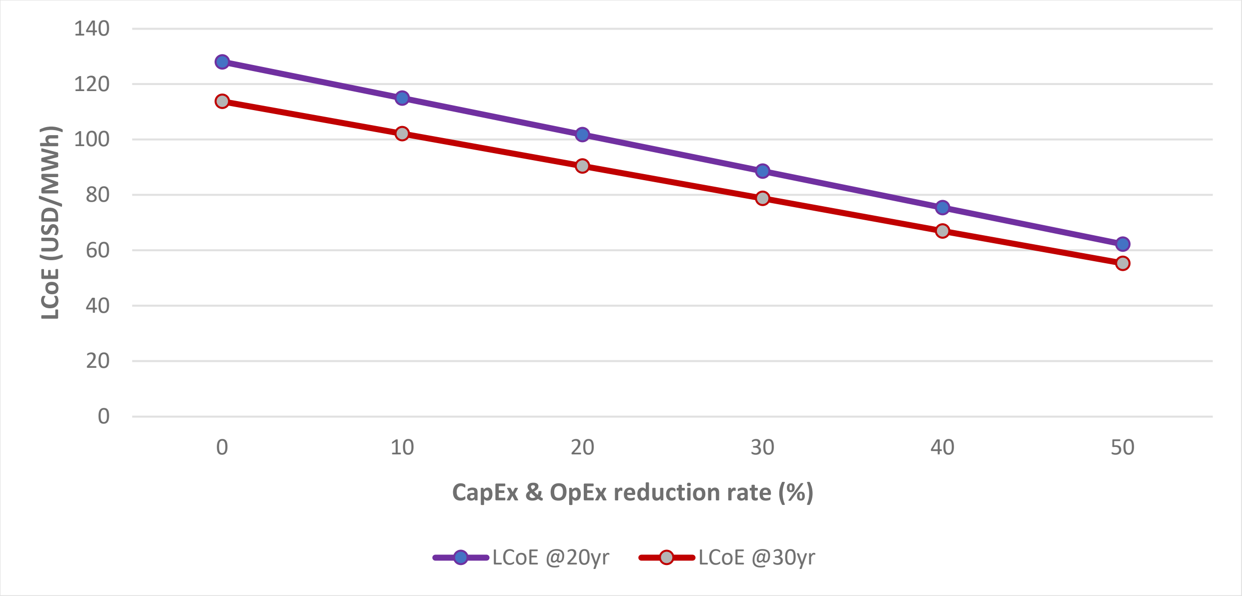

Figure 7. LCoE at different CapEx & OpEx reduction rates

Figure 7 indicates the changes in the LCoE as the CapEx and OpEx decrease. The change in SMP was omitted because it exerted no effect on LCoE. As shown in the graph below, the overall LCoE also decreases as the CapEx and OpEx decrease. When the reduction rate of CapEx and OpEx was 0%, and the operating period of the offshore wind power plant was 30 years, the LCoE decreased by approximately 11.17% based on 20-year operation. Although this gap gradually decreased with a decrease in the reduction rate of CapEx and OpEx from 0 to 50%, the decrease was not significant. When the reduction rate was 50%, the LCoE decreased by approximately 11.07% based on a 20-year operation.

5. Discussion & Conclusion

5.1. The need to set the maximum value of REC weight

As presented in *4.1. Comparison of SMP + 1 REC, LCoE and IRR at different REC Weights*, according to the formula for calculating the compound weight of offshore wind power linkage distance and water depth announced by the Korea Energy Agency as of September 2022, the limit for the maximum value of the combined weight is not specified. Thus, if the project assumptions of this study (i.e., a linkage distance of 70 km and a water depth of 150 m) are applied, the final 4.6 REC weight can be obtained. If a REC weight of 4.6 is given, the SMP + 1 REC, (i.e., the revenue consumed by the power producers per 1 MWh of electricity produced from wind power) is USD 397.46, which is approximately 5.7 times higher than the monthly SMP (USD 69.84). In this case, the expected IRR is 27.45%. If the IRR is 27.45%, no power producers will be reluctant with their business. Because this IRR is an unrealistic value, the South Korean government would not sign a fixed contract with a power producer based on a REC weight of 4.6. As indicated in this study, a fluctuation in SMP is an important factor in determining the profitability of offshore wind power projects. To accurately calculate the profitability of offshore wind power projects and avoid confusion, the government should designate and announce the maximum value of REC weight to power producers.

Moreover, as shown in *Figure 4,* although the IRR decreases with a decrease in the REC weight, the IRR is 12.46% when the REC weight is 1.7. This indicates that business feasibility is still sufficient. Therefore, there is a need to adjust the calculation method of the REC weight by comparing the profits of the demonstration complex.

5.2. Cost of a floating offshore wind project in combination with a green hydrogen

This study proposed the relationship between a floating offshore wind farm and a hydrogen power plant as a profitable method for ensuring the profitability of offshore wind farm without government support. Particularly, the utilization of electricity wasted owing to curtailment of the offshore wind plant would increase the overall profitability to a noticeable level. However, as shown in *4.1. Comparison of SMP + 1 REC, LCoE and IRR at different REC Weights*, the connection of the green hydrogen project with floating offshore wind power increased the LCoE of the overall project and decreased the IRR with an increase in the capacity of the PEM electrolyser and the hydrogen production. This result indicates that the feasibility of the project is low. Although the operating period of the power plant was divided into 20 and 30 years for calculation, the same trend was observed. Why did this result appear?

The capacity of the PEM electrolyser varies depending on the curtailment rate of offshore wind power, that is, as the curtailment rate increases, the amount of electricity generated through offshore wind power decreases and the amount of hydrogen produced through the electrolyser increases. This can be easily understood if the revenue generated by wind power and hydrogen power generation is calculated using 1 MWh of electricity. Using 1 MWh of electricity, approximately 17.24 kg of hydrogen can be produced, which corresponds to approximately KRW 103,448. Excluding the ammonia transport cost of 1,800 KRW/kg H2, hydrogen produced using 1 MWh of electricity can be utilized to generate a profit of approximately KRW 72,414. This amount is less than the 83,910 KRW/MWh for the SMP.

5.3. Effect of IRR on decreases in CapEx & OpEx and increases in SMP

As mentioned previously, the factors most directly related to the profitability of floating offshore wind power are the prices of CapEx and OpEx, and SMP. To verify this, this study examined the change in IRR with a decrease in CapEx and OpEx, and an increase in SMP in *4.3. Comparison of SMP and IRR at different SMP increase rate and CapEx & OpEx reduction rate*.

According to five floating offshore wind study cases conducted by NREL, the CapEx of floating offshore wind power was predicted to decrease by an average of approximately 35% from 2019 to 2035 (Beiter, Philipp, Walter Musial, Patrick Duffy, Aubryn Cooperman, Matt Shields, Donna Heimiller, and Mike Optis, 2020). Based on this, the change in the IRR was examined when the reduction ratios of CapEx and OpEx are 30 and 40%. When the reduction ratios of CapEx and OpEx are 30%, and the operating period of the wind power farm is 30 years, the price of SMP must increase by 11% to achieve an IRR of 6.77%, which exceeds 6.74% of the discount rate. The SMP price in this case is 77,153 USD/MWh. When the reduction ratios of CapEx and OpEx are 40%, and the operating period of the power generation complex is 30 years, the IRR becomes 7.23% without an increase in SMP. Under this condition, power producers will be able to make profit without government support.

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