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A Comparative Analysis of Economics of PMSG and SCSG Floating Offshore Wind Farms

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Abstract: The biggest obstacle to using a permanent magnet synchronous generator (PMSG) for a floating offshore wind turbine (FOWT) is the weight. A superconducting synchronous generator (SCSG) can be an alternative to this problem. In this paper, first, the weight and volume of a 10 MW class PMSG and SCSG for a large floating offshore wind farm (FOWF) were compared. Reflecting this, the economic feasibility of a 200 MW class FOWF based on a semi-submersible platform was compared and analyzed. The levelized cost of energy (LCOE) was used to compare the economics of the two types of FOWF, and the LCOE of the SCSG type FOWF was 6 (USD/MWh) more expensive than that of the PMSG type FOWF. However, if the superconducting wire price is reduced by 40% compared to the current price, the economic feasibility of the SCSG type FOWF can be secured. Considering only the weight, the SCSG type FOWF is far superior to the PMSG type FOWF. With the trend of falling superconducting wire prices and improving critical current, the SCSG type FOWF is expected to become a definite alternative to large-capacity wind farms, and the economic feasibility is expected within the next five years.

Keywords: economic feasibility; floating offshore wind farm; levelized cost of energy; permanent magnet synchronous generator; superconducting synchronous generator

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1. Introduction

Wind power has now become the world's fastest-growing source of renewable energy. According to the US Department of Energy, wind energy is expected to contribute to a significant portion of the U.S. electricity supply over the next 20 years [1]. Currently, the development of offshore wind technology, which has many advantages over the onshore wind, is actively progressing, and accordingly, the installed capacity is continuously increasing. However, if the support of the wind turbine is fixed to the seafloor, installation becomes difficult when the water depth is more than 50 m. Floating offshore wind turbine (FOWT) systems are no longer limited to maximum depth constraint (50 m) because they can be deployed in deep-sea areas with high wind energy utilization potential [2]. In terms of the design of a FOWT, as the weight of the wind generator increases, the size of the platform increases, and the total construction cost also increases. Therefore, in order to reduce the capital expenditure (CAPEX), an effective design technology that can reduce the volume and weight of the entire platform is required. The permanent magnet synchronous generator (PMSG) is most often used for MW class wind power generation because of its high efficiency [3–7]. However, the development and installation of wind turbines of 10 MW or more suffer from the high weight of the wind generator. As an alternative to solving these problems, a superconducting synchronous generator (SCSG) has been proposed. The high magnetic field strength generated by the superconducting coil is expected to provide a lighter and more compact direct-drive design than those implemented in copper coils, permanent magnets, and magnetic iron [8]. In the case of a superconducting generator, the EcoSwing project was carried out in Europe until 2019 [9]. In this project, a full-scale 3.6 MW direct-drive SCSG was designed, manufactured, and tested.

The SCSG has the advantages of having a small volume, lightweight, and high efficiency compared to the conventional PMSG type generators. However, compared to the conventional generator, the SCSG has a cost issue because it includes a superconducting wire and a cooling system, and a superconducting wind turbine is almost twice the price of a conventional wind turbine. To prove the suitability of FOWT, it is necessary to compare the economic feasibility of the PMSG and SCSG types FOWTs. Regarding the economic analysis of wind turbines using various types of generators, reference [10] estimated the CAPEX of a 10 MW direct-drive wind turbine using only an SCSG, without comparing it to the PMSG type. Reference [11] also presented a model related to design cost and scaling that can be used when developing an SCSG, but they did not compare with the PMSG method. Reference [12] aimed to develop a methodology for determining the economic feasibility of a floating offshore wind farm (FOWF) but did not compare different types of generators. Reference [13] conducted a study comparing 12 MW class PMSG type and SCSG type wind turbine, but an economic analysis was not conducted including the floating structures. In order to appeal to the economic feasibility of a large-scale FOWF, it is necessary to compare the economic feasibility of the SCSG type FOWF with other existing generator types.

This paper compared the economic feasibility of FOWFs consisting of two types of generators. In order to compare economic feasibility, the structure of generators of the PMSG and SCSG types was investigated, and the scaling equation was studied to scale up the capacity to 10 MW. The levelized cost of energy (LCOE) has been calculated taking into account the different types of generators, which means a measure from an economic point of view used to compare the lifetime costs of electricity production. Depending on the type of FOWT, there are differences in the CAPEX and operating costs, so we analyzed and compared the economic feasibility of each floater type. For the PMSG and SCSG types FOWTs, the cost of the FOWT was calculated by considering the difference in the weight and volume of the turbine. Moreover, the economic feasibility of a FOWF was analyzed based on the composition of the wind farm. The nacelle mass of the 10 MW class PMSG type FOWT is 542.6 tons and that of the SCSG type FOWT is 335.0 tons. The reduction in nacelle mass has reduced the cost of wind turbine-related items including transportation and installation, mooring systems, and infrastructures. The LCOE of the PMSG type FOWF was calculated as 206.78 (USD/MWh) and that of the SCSG type FOWT was calculated as 212.88 (USD/MWh), due to the reduction in turbine weight. Looking at the trend of superconducting wire prices over the past five years, the price is falling rapidly. Considering this trend of the price decline, it is possible to cut the price by 40% in the near future. Then, the LCOE of the SCSG type FOWT is expected to be 205.56 (USD/MWh), securing the economic feasibility. The lighter weight makes it possible to operate the wind turbine more safely, and the design, transport, and installation of the tower that can support the nacelle become easier. Therefore, we are confident that the SCSG can be an effective alternative to large-scale FOWFs.

2. A 10 MW Class FOWT System

2.1. The FOWF Platforms

The current FOWF in operation is Hywind Scotland 30 MW, the world's first FOWF [14]. It consists of 6 MW class wind turbines using the spar-buoy concept. Moreover, WindFloat Atlantic, the world's first semi-submersible FOWF is fully operated with a total installed capacity of 25 MW using an 8.4 MW wind turbine [15]. In addition to this, the construction of the 88 MW Hywind Tampen using the Siemens Gamesa 8 MW turbine with a spar-buoy floating system began in October 2020 [16], and a 10 MW FOWT is still under development.

In this paper, we reviewed several platform types to design a 10 MW FOWT system. The FOWT systems are generally classified into spar-buoy, semi-submersible, and tension leg platforms (TLP) [17–20], as shown in Figure 1. As a characteristic of each FOWT system, the spar-buoy has a very large cylindrical buoy, and the semi-submersible is a structure that secures the necessary stability by combining the main principles of spar-buoy + TLP. The TLP consists of a semi-submersible in a highly buoyant structure, and several tensioned mooring lines are attached to the structure and anchored to the seabed to increase buoyancy and stability [20].

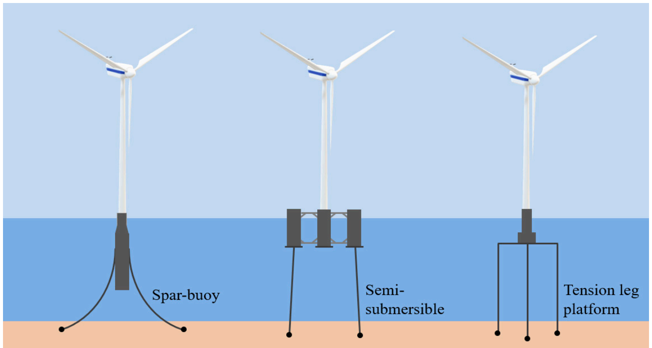

Figure 1. Three major types of floating offshore wind turbine (FOWT).

The 10 MW FOWT platform is being developed at the University of Ulsan as part of a joint research project in Korea based on the National Renewable Energy Laboratory (NREL) 5 MW floating concept [21–24]. Analysis by type showed that the spar-buoy had greater nacelle acceleration, load on wind turbines, and platform pitch than the semi-submersible and TLP, and mooring tension of the TLP was greater than that of the semi-submersible and spar-buoy. The semi-submersible was analyzed to be the most stable than the spar-buoy and TLP. Based on these findings, the semi-submersible type was selected as the platform type of a 10 MW FOWT.

Table 1 shows the specifications of the PMSG and SCSG designed with semi-submersible FOWT. The mass of the PMSG FOWT excluding the blade was calculated by referring to 10 MW of International Energy Agency (IEA) fixed offshore wind turbine [25]. The blade mass of the PMSG FOWT was calculated as the same value as the SCSG FOWT, and the mass of the SCSG FOWT was calculated through a joint research project [21].

Table 1. Data of the 10 MW class FOWT for the platform design.

Items	PMSG Type 10 MW	SCSG Type 10 MW
Rated power [MW]	10	10
Blade radius [m]	89.1	89.1
Cut-in wind speed [m/s]	4	3
Rated wind speed [m/s]	11	11.3
Cut-out wind speed [m/s]	25	25
Single blade mass [kg]	32,512	32,512
Nacelle mass [kg]	542,600	335,000
Tower mass [kg]	628,442	610,084

2.2. *Characteristic Comparison of the PMSG and SCSG Applied to 10 MW Class Wind Turbines*

The larger the unit capacity of a wind turbine has more advantages, but as its weight increases, it is very difficult to install and maintain a tall tower capable of supporting a huge nacelle. Moreover, it is more difficult to install and operate at sea, not on land. In addition, as mass is added, the total cost also increases, limiting commercial viability. The SCSG has caught the attention of researchers as a solution to this problem. The SCSG can overcome the limitations of conventional PMSG through its lightweight and compact volume. At the same length, superconducting wires can acquire more magnetic fields than copper wires, making them more compact, which leads to easy transportation, reduced installation and maintenance costs. Figure 2 shows the size comparison of the PMSG and SCSG of the same capacity.

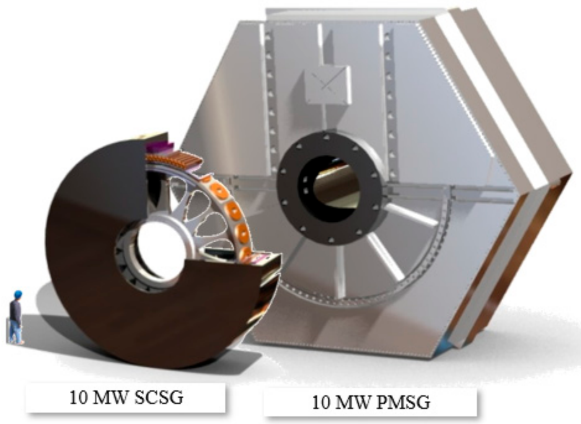

Figure 2. Comparison of the size of the permanent magnet synchronous generator (PMSG) and superconducting synchronous generator (SCSG) [14].

By applying the SCSG, it is possible to design nacelles and supporting structures that can be safely operated by reducing the weight, and in the case of the FOWT, the size of the platform is reduced, which affects the reduction of CAPEX. In addition, rare earth requirements increase significantly with increasing the PMSG capacity, which leads to economic dependence on countries that exclusively own these resources. This problem can be reduced by using the SCSG. High-capacity wind turbines tend to use gearless types due to gearbox maintenance issues. The 10 MW gearless type generator uses a synchronous generator, so it is much larger and heavier than a geared type generator. Therefore, in the event of a breakdown of a large and heavy generator, it takes more time to repair, and due to the weight of the generator, there are few cranes that can lift a 10 MW PMSG. The SCSG requires a cooling system to maintain cryogenic temperatures, resulting in additional Operation & Maintenance (O&M) costs for the cooling system compared to the PMSG, which does not require a low-temperature cooler. In order to compare the PMSG and SCSG in terms of cost, we calculated the generator manufacturing cost. In the case of the PMSG, since the price of the generator calculated by the scaling equation is different from the price trend of the large-capacity generator, it was corrected through literature review. The total cost of 10 MW class PMSG was estimated at USD 7 million, and that of the SCSG was calculated taking into account the price of the SCSG components [26]. The SCSG's rotor consists of 10 modules and includes four coils per module. Table 2 shows the price of one rotor module.

The price of the SCSG, taking into account all components, the stator, and 10 rotor modules, is given in Table 3. Comparing the price of the two generators, the PMSG price is 7.0 (MUSD) and the SCSG price is 14.2 (MUSD), respectively.

The weights of the PMSG and SCSG were 323 tons and 120 tons, respectively. The SCSG weight was close to one-third of the PMSG weight, but the price doubled as shown in Figure 3.

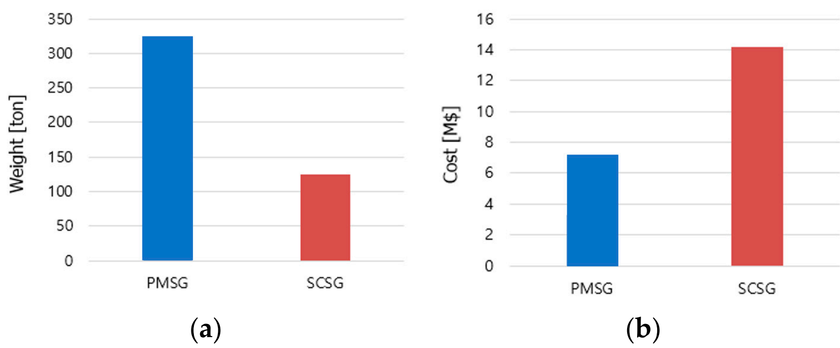

Figure 3. Comparison of the PMSG and SCSG; (**a**) weight of the PMSG and SCSG and (**b**) cost of the PMSG and SCSG.

Table 2. Cost of one rotor module for 10 MW class SCSG.

Main Part	Components/Remark	Quantity	Cost (USD)
Rotor module (1 module)	Cryostat	1	62,730
	Bobbin	12	386,400
	Current lead	2	1000
	Current feedthrough terminal	2	692
	Terminal joint	2	300
	FRP supporter	8	10,702
	Radiation shield	1	4000
	Vacuum pump	1	4000
	Temperature sensor	20	11,800
	Hall sensor (low temperature)	4	6400
	Vacuum sensor and Monitor	1	1500
	Current feed through	3	1050
	Superconducting wire	9844	375,259
	MLI	4	302,946
	Others (Nitrogen, tools, and accessories)	4	63,820
Total cost			1,232,599

Table 3. Cost for the 10 MW class SCSG.

Main Part	Material	Weight/Unit	Cost (USD)
Rotor body (Back iron)	35PN250	10,600 kg	110,770
Rotor modules (rotor poles)	HTS module	10 modules	12,325,986
Stator coils	Copper	25,900 kg	414,400
Stator body	35PN250	40,800 kg	426,360
Cryocooler	Stirling cryocooler		854,511
Torque disk		3500 kg	45,500
Generator cover		13,500 kg	15,337
Total cost			14,192,863

The big difference in price between the PMSG and SCSG is due to the price of superconducting wire. Figure 4 shows the ratio of the SCSG generator components to cost. The 10 MW class SCSG was designed with superconducting wires from two companies in consideration of economy and performance. The superconducting wire was composed of 4182 m from company A and 5662 m from B. The average price of a superconducting wire applied to the 10 MW SCSG is USD 76.6 per meter. Therefore, the total price of the superconducting wire applied to the 10 MW SCSG design is USD 0.68 million, accounting for about 55% of the price of one rotor module and 50% of the total price of the SCSG. For this reason, the SCSG still has an obstacle to commercialize in terms of price.

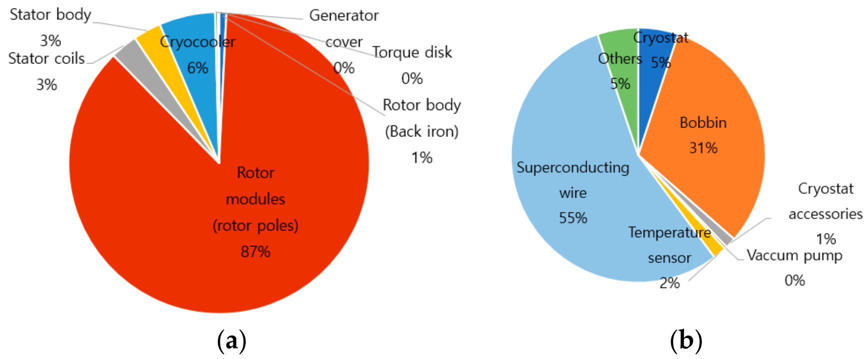

Figure 4. Cost ratio of the SCSG and the rotor module; (**a**) cost ratio of components in the generator and (**b**) cost ratio of components in the rotor modules.

2.3. Economic Feasibility Study of the PMSG Type FOWF and the SCSG Type FOWF

To analyze the economic feasibility of a FOWF with different types of generators, the LCOE of each FOWF was calculated. The LCOE is a measure of the average net present cost of electricity generation for a generating plant over its lifetime [27]. The LCOE is calculated as the ratio of all the discounted costs over the lifetime of an electricity generating plant divided by the discounted sum of the actual amount of energy delivered [28].

The LCOE was calculated as follows:

$$LCOE = \frac{ICC \times FCR}{AEP} + AOE \quad (1)$$

where

FCR = fixed charge rate (1/year)
ICC = initial capital cost (USD)
AEP = net annual energy production (kWh/year)
AOE = annual operating expenses = *(LLC* + *O&M* + *LRC)/AEP*
LLC = land lease cost
O&M = levelized operating and management cost
LRC = levelized replacement/overhaul cost

The PMSG and SCSG type FOWTs were scaled up based on the NREL 5 MW OC4 wind turbine considering the floating type. The 10 MW FOWT has an aerodynamic rotor diameter of 178.2 m and a rated rotational speed of 9.69 rpm. Both types of generators were considered direct-driven. The specifications of a 10 MW class FOWT are shown in Table 4.

Table 4. Specifications of the 10 MW class FOWT.

Items	Value
Rated power [MW]	10
Rated wind speed [m/s]	11.3
Rotation speed [rpm]	9.69
Blade length [m]	89.1
Rotor diameter [m]	178.2
Hub height [m]	120
Tower height [m]	102.5
Mass density of air [kg/m^3]	1.225

The FOWF has a capacity of 200 MW and is located 58 km from the coast. Components of the FOWF include FOWT, converter station, and submarine cables. Considering the distance to the shore, the transmission system was chosen as an High Voltage Direct Current (HVDC) system. Collection and transmission systems voltage levels were chosen as 66 kV and 154 kV, respectively, taking into account the cable rating as shown in Figure 5.

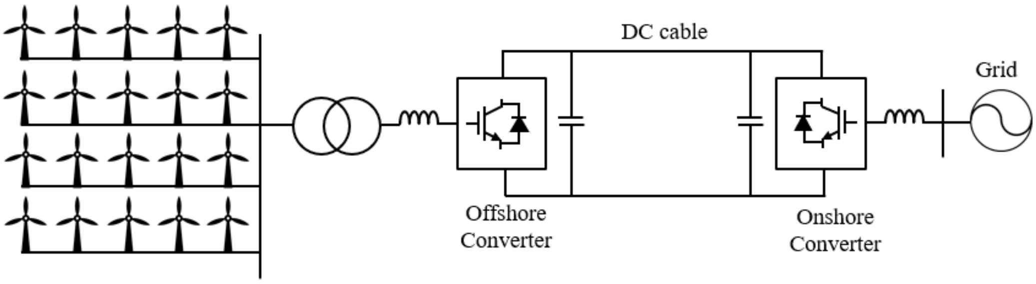

Figure 5. Configuration of the 200 MW monopolar HVDC system for the FOWF.

The offshore wind farm topologies include a radial topology, a single-sided ring, a double-sided ring, and a star topology [29]. Topologies for the offshore wind farm collection system are proposed by previous researches [29–31]. The number of components of a FOWF depends on the topology. In this study, a radial configuration that is economical and easy to install was selected. To analyze the economic feasibility of a 10 MW class wind turbine, the cost was calculated based on the scaling equation studied in [32,33]. The platform of the FOWT for economic analysis is a semi-submersible type. For economic analysis, turbine capital cost (TCC), balance of station cost (BOS), initial capital cost (ICC), levelized replacement cost (LRC), land lease cost (LLC), operation and maintenance cost (O&M), capacity factor (CF), annual energy production (AEP), fixed-charge rate (FCR), the rotor diameter of the wind turbine (D_{WT}), and the capacity of the wind turbine (C_{WT}) were considered. The wind turbine components and the cost formulas for calculating the TCC are shown in Table 5. The cost formulas were referenced the NREL wind turbine design cost and scaling model, and the 10 MW wind turbine data were used to calculate the TCC by the scaling equation.

Table 5. Cost formulas for turbine capital cost (TCC) of the FOWT [32].

Components		Mass Formulas	Cost Formulas
Rotor	Blades	-	$\frac{\left(0.4019 D_{WT}^{3} - 955.24 + 2.7445 D_{WT}^{2.5025}\right)}{(1-0.28)}$
	Hub	-	$hub\ mass \times 4.25$
	Pitch bearing	$0.954 \times total\ three\ blade\ mass + 491.31$	$2.28 \times \left(0.2106 \times D_{WT}^{2.6578}\right)$
	Pitch system	$(Total\ pitch\ bearing\ mass \times 1.328) + 555$	
	Spinner, Nose cone	$18.5 \times D_{WT} - 520.5$	$Nose\ cone\ mass \times 5.57$
Drive train, Nacelle	Low-speed shaft	$0.0142 \times D_{WT}^{2.888}$	$0.01 \times D_{WT}^{2.887}$
	Bearings	$D_{WT} \times 8/600 - 0.033 \times 0.0092 \times D_{WT}^{2.5}$	$2 \times bearing\ mass \times 17.6$
	Mech brake	Brake coupling cost/10	$(1.9894 \times C_{WT}\ [kW] - 0.1141)$
	Generator	-	$C_{WT}\ [kW] \times 219.33$
	Variable speed electronics	-	$79 \times C_{WT} \times 1000$
	Yaw drive and Bearing	$1.6 \times \left(0.0009 \times D_{WT}^{3.314}\right)$	$2 \times \left(0.0399 \times D_{WT}^{2.964}\right)$
	Main frame	$1.228 \times D_{WT}^{1.953}$	$627.28 \times D_{WT}^{0.85}$
	Platforms and Railings	$0.125 \times mainframe\ mass$	$mass \times 8.7$
	Electrical connections	-	$40 \times C_{WT} \times 1000$
	Hydraulic and cooling system	$0.08 \times C_{WT} \times 1000$	$12 \times C_{WT} \times 1000$
	Nacelle cover	$11.537 \times C_{WT} \times 1000 + 3849.7$	$(nacelle\ cost/10)$
Control, safety system, condition monitoring		-	55,000
Tower		$0.3973 \times swept\ area \times hub\ height - 1414$	$Tower\ mass \times 1.50$
Marinization		-	$13.5\%\ of\ turbine\ and\ tower\ costs$

The CAPEX for wind turbines includes the TCC and BOS. The BOS of a wind turbine represents the total cost excluding turbine cost. The BOS was calculated including the substructure components based on a 10 MW wind turbine design [33]. The cost formulas for calculating the BOS are shown in Table 6.

Table 6. Cost formulas for the balance of station cost (BOS) of the FOWTs [32,33].

Components	PMSG Type FOWT	SCSG Type FOWT
Contingency	1,269,583 $\times C_{WT}$	1,269,583 $\times C_{WT}$
Insurance during construction	43,858 $\times C_{WT}$	43,858 $\times C_{WT}$
Transport and installation	272,140 $\times C_{WT}$	137,446 $\times C_{WT}$
Electrical interconnection	490,520 $\times C_{WT}$	490,520 $\times C_{WT}$
Mooring system	65,787 $\times C_{WT}$	39,473 $\times C_{WT}$
Substructure	1,051,115 $\times C_{WT}$	630,669 $\times C_{WT}$
Project development	173,124 $\times C_{WT}$	173,124 $\times C_{WT}$
Port and staging equipment	20,000 $\times C_{WT}$	12,000 $\times C_{WT}$
Personal access equipment	$60,000 \times number\ of\ turbine$	$60,000 \times number\ of\ turbine$
Surety bond	$ICC \times 0.03$	$ICC \times 0.03$

Table 7 shows the items required for the calculation of the LCOE. Among the items, the ICC is the initial cost, and the LRC, the LLC, and the O&M are the factors of the annual cost. The CF is the average output power divided by the maximum power, and the AEP is the annual energy production. The FCR is covered by construction financing, financing fees, debt, equity returns, depreciation, income tax, property tax and insurance.

Table 7. Cost formulas for levelized cost of energy (LCOE) calculation of the wind turbine [32,34].

Items	Cost Formulas	Remark
ICC	$TCC + BOS$	-
LRC	$17 \times C_{WT} \times 1000$	The SCSG is added by 20% due to the cost of replacing the cooling system
LLC; offshore bottom lease cost	$0.00108 \times AEP$	-
O&M	$4.5907\ln(x) + 48.827$ (x: water depth [m])	The SCSG is added by 15% due to the cooling system O&M cost
CF	44.3%	Selected by Weibull distribution analysis
AEP	$365 \times 24 \times CF \times C_{WT} \times 1000$	-
FCR	10.4%	-

A contingency cost formula was defined considering the FOWT price is USD 4.9 million per MW due to the early stage domestic manufacturing technology of the FOWT. Due to the cooling system, the SCSG type FOWT adds 20% and 15% of the LRC and O&M costs, respectively [34]. In addition, the capacity factor of the FOWT was calculated as 44.3% through the Weibull distribution analysis based on the wind condition data measured at the sea of Ulsan, Korea [35]. The expansion from the floating system to the wind farm includes collection systems, converter stations, and transmission systems. Each element price was investigated to calculate including the components of the wind farm as shown in Table 8. The price of the dynamic submarine cable used in the FOWT was calculated taking into account the price 30–50% higher than the fixed type [36].

Table 8. Cost formulas for the FOWF components [37,38].

Classifications	Components	Cost Formulas
Collection system	AC cable	$1,070,000 \times collection\ system\ cable\ length\ per\ km$
	Collection cable installation cost	$330,000 \times collection\ system\ cable\ length\ per\ km$
Converter station	Converter station	$130,000 \times wind\ farm\ rating \times 2 \times 10^{-6}$
Transmission system	HVDC cable	$620,000 \times transmission\ system\ cable\ length\ per\ km$
	Transmission cable installation cost	$494,000 \times transmission\ system\ cable\ length\ per\ km$

To calculate the operating expenditure (OPEX) of the FOWF, the items related to the operation and maintenance of wind turbines and cables were considered as shown in Table 9.

Table 9. Items used to calculate the operating expenditure (OPEX) of the FOWF.

Classifications	Items
Wind turbine	Wind turbine O&M cost
Wind farm	Collection cable loss cost Cable O&M cost Energy not supplied cost

The O&M cost of the wind turbine was calculated based on the cost equation in the NREL report [39]. Assuming that the water depth is appropriate, the O&M cost of the semi-submersible type FOWT can be calculated as Equation (2).

$$y = 4.5907ln(x) + 48.827 \quad (2)$$

where, x is the water depth and y is the O&M cost.

The collection cable loss cost was calculated as Equation (3) based on the AC cable [40].

$$C_{in,loss} = C_E \times 8760 \times 10^{-5} \times \sum_{k=1}^{N_{in}} 3\left(\frac{CF \cdot P_{Feeder,k}}{\sqrt{3}V_{in}pf}\right)^2 R_{in} \cdot l_{in,k} \quad (3)$$

where, $C_{in,loss}$ is the collection cable loss cost, C_E is the energy generation cost per kWh, N_{in} is the number of collection system cable feeders, CF is the capacity factor, $P_{Feeder,k}$ is the sum of the rated capacity of the wind turbine installed at the kth feeder, V_{in} is the internal network voltage level, pf is the power factor, R_{in} is the resistance per unit length of the collection system cable, and $l_{in,k}$ is the kth collection system feeder cable length.

The cable O&M cost was calculated as Equation (4).

$$C_{m,t} = C_{repair} \times \left(\sum_{k=1}^{N_{in}} \lambda_{in} l_{in,k} + \lambda_{ex} l_{ex} N_{ex}\right) \quad (4)$$

where, $C_{m,t}$ is the cable O&M cost, C_{repair} is the repair cost in case of one failure of cable, λ_{in} *and* λ_{ex} are the annual failure rate per unit length of the collection system and transmission system cable, l_{ex} is the transmission cable length, and N_{ex} is the number of transmission system cable lines.

The cost of energy not supplied was calculated as Equations (5) and (6).

$$C_{ENS} = C_E \times 10^{-5} \times \left(\sum_{k=1}^{N_m} CF \cdot P_{Feeder,k} U_{in,k} + CF \cdot P_{OWF} U_{ex}\right) \quad (5)$$

$$U = 8760 \times \frac{\lambda}{\mu} \times l \quad (6)$$

where C_{ENS} is the cost of energy not supplied, P_{OWF} is the capacity of the wind farm, and $U_{in,k}$ and U_{ex} are the collection system and the transmission system cable repair rates.

3. Study Results and Discussions

3.1. The CAPEX of the PMSG and SCSG Type FOWFs

To analyze the economic feasibility of the 200 MW class FOWF, it is necessary to calculate the CAPEX of the FOWT constituting the wind farm. The CAPEX of the PMSG and SCSG type FOWTs can be estimated based on the cost scaling formulas [32,33], as shown in Table 10. In the case of the SCSG type FOWT, the cost scaling was performed considering that the nacelle mass was close to that of the 6 MW conventional PMSG type wind turbine due to the reduction of top head weight. Items including nacelle cover, mooring system, and substructure were scaled to 6 MW. Transportation and installation cost was calculated as 20% of the fixed offshore wind turbine [41].

Table 10. The capital expenditure (CAPEX) of the 10 MW class PMSG and SCSG types FOWTs (unit: USD).

Components		PMSG Type FOWT Cost	SCSG Type FOWT Cost
Rotor	Blades	2,047,137	2,047,137
	Hub	340,000	340,000
	Pitch mechanism and bearing	461,164	461,164
	Spinner, Nose cone	15,463	15,463
Drive train, Nacelle	Low speed shaft	315,044	315,044
	Bearings	321,641	174,240
	Mech brake	19,894	19,894
	Generator	7,017,189	14,192,863
	Variable speed electronics	790,000	790,000
	Yaw drive and Bearing	318,361	318,361
	Main frame	51,373	51,373
	Platforms and Railings	33,239	33,239
	Electrical connections	400,000	400,000
	Hydraulic and cooling system	120,000	120,000
	Nacelle cover	115,417	73,072
Control, safety system, condition monitoring		55,000	55,000
Tower		942,663	915,126
Marinization		145,425	145,425
TCC		14,034,897	20,755,943
Contingency		12,695,825	12,695,825
Insurance during construction		438,583	438,583
Transport and installation		2,721,400	1,374,464
Electrical interconnection		4,905,205	4,905,205
Mooring system		657,875	394,725
Substructure		10,511,151	6,306,691
Project development		1,731,249	1,731,249
Port and staging equipment		200,000	120,000
Personal access equipment		60,000	60,000
Surety bond		930,000	1,500,000
BOS		35,271,288	29,526,742
ICC		49,306,185	50,282,685

The 10 MW PMSG type FOWT was calculated as 49 (MUSD), and the 10 MW SCSG type FOWT was calculated as 50 (MUSD). Including the calculated FOWT, the CAPEX of the 200 MW class wind farm consisting of 20 turbines of 10 MW wind turbine was calculated based on the cost formulas of the FOWF components as shown in Table 11.

Table 11. CAPEX of the 200 MW class PMSG and SCSG types FOWFs (unit: USD).

Classifications	Components	PMSG Type FOWF Cost	SCSG Type FOWF Cost
Wind turbine	FOWTs (20 turbines)	986,123,706	1,005,653,704
Collection system	AC cable	31,244,000	31,244,000
	Collection cable installation cost	9,636,000	9,636,000
Converter station	Converter station	52,000,000	52,000,000
Transmission system	HVDC cable	143,840,000	143,840,000
	Transmission cable installation cost	114,608,000	114,608,000
Total cost		1,337,451,706	1,356,981,704

Except for the FOWT, the wind farm component prices were the same for the PMSG type and the SCSG type, but because the price of the SCSG type FOWT is slightly higher, the total cost of the 200 MW class FOWF was about 20 (MUSD) higher for the SCSG type than the PMSG type.

3.2. *The OPEX of the PMSG and SCSG Type FOWFs*

The OPEX of the PMSG and SCSG types FOWFs can be estimated based on the OPEX cost scaling formulas. Cost data is required for price calculation, which is shown in Table 12. The OPEX of the 200 MW class FOWF was calculated by the wind turbine O&M equation shown in Table 7 and Equations (2)–(6), and calculation results are shown in Table 13.

Table 12. Data for calculating the OPEX of the FOWF.

Classifications	Items	Value
Wind farm	Capacity of the wind farm (MW)	200
	Voltage level of the collection system (kV)	66
	Voltage level of the transmission system (kV)	154
	Power factor	0.95
Collection system cable	Cable installation cost (C_{in}) (MUSD/km)	0.48
	AC resistance (Ω/km)	0.067
	Failure rate (times/year·km)	0.000705
	Repair rate (times/year)	6.083
Transmission system cable	Cable installation cost (C_{ex}) (MUSD/km)	0.61
	Failure rate (times/year·km)	0.0011
	Repair rate (times/year)	6.404
Energy generation cost (USD/kWh)		0.073
Cable repair cost (MUSD/km)		0.65

Table 13. OPEX of the PMSG and SCSG types FOWFs (unit: USD/year).

Items	PMSG Type FOWF Cost	SCSG Type FOWF Cost
Wind turbine O&M cost	13,493,455	15,517,473
Collection cable loss cost	626,187	626,187
Cable O&M cost	551,877	551,877
Energy not supplied cost	2,485,020	2,485,020
Total cost	17,156,539	19,180,557

3.3. *Comparison Results of Economic Analysis of the PMSG and SCSG Type FOWFs*

The CAPEX of the PMSG and SCSG type FOWTs were compared, as shown in Figure 6. In the case of the TCC, the SCSG type FOWT was about 1.1 (MUSD/MW) higher than that of the PMSG type FOWT. In the case of the BOS, 0.57 (MUSD/MW) was saved due to the reduction of the top head weight of the SCSG type. However, the total CAPEX of the SCSG was about 0.54 (MUSD/MW) higher than that of the PMSG.

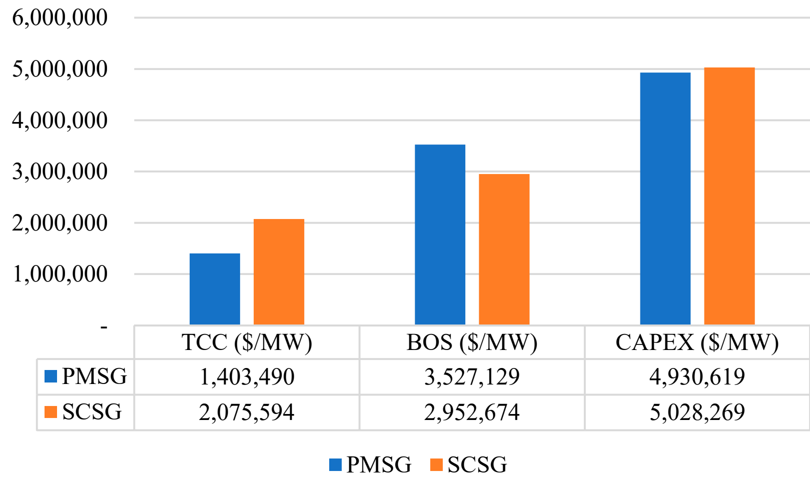

Figure 6. The CAPEX of the PMSG and SCSG type FOWTs.

When comparing the OPEX, the SCSG type FOWT adds additional replacement cost and maintenance cost for the cooling system. Therefore, the SCSG type FOWT was about 1.1 (MUSD/MW·year) higher than the PMSG type FOWT in total OPEX, as shown in Figure 7.

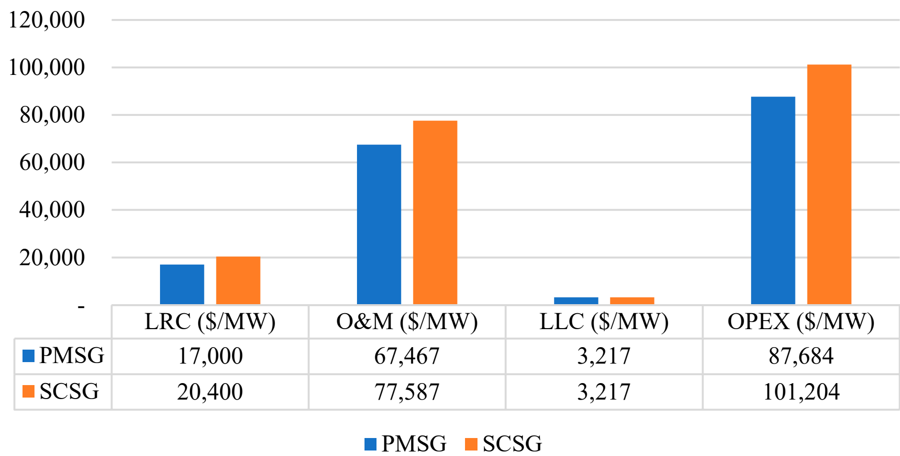

Figure 7. The OPEX of the PMSG and SCSG type FOWTs.

A comparison study of the PMSG type FOWF and the SCSG type FOWF was conducted to evaluate the economic feasibility of a large-scale FOWF, and the results are shown in Table 14. The LCOE of the FOWF was calculated and compared by reflecting the components of the FOWF.

To determine the possibility of securing the economic feasibility of the SCSG type FOWF, the cost trend of superconducting wire, which has a great influence on the economy, was reviewed. Superconducting wire prices have fallen from USD 150/kA m in 2014 to USD 83/kA m in 2019 (kA m: the price of a 1 m wire with a critical current of 1 kA), as shown in Table 15 [42,43]. The drop in superconducting wire prices is due to an increase in critical current. According to SuNAM, the critical current for a 10 mm superconducting wire was 355 A in 2012, but now it is 616 A, an increase of 74% as shown in Figure 8, which has become a factor that could reduce the cost of the wire to 55.33%. Therefore, it is expected that the price will reach 40% lower than the current price within the next five years, and based on this, the LCOE was calculated by applying 40% of the wire cost to confirm the economic feasibility of the 10 MW generator. As a result, the LCOE of the SCSG type FOWF was 1.2 (USD/MWh) lower than the PMSG type FOWF as shown in Table 16.

Table 14. The LCOE of the PMSG and SCSG type FOWFs.

Items	PMSG Type FOWF	SCSG Type FOWF
Wind farm capacity (MW)	200	200
TCC (USD/MW)	1,403,490	2,075,594
BOS (USD/MW)	3,527,129	2,952,674
CAPEX (USD/MW)	6,687,259	6,784,909
OPEX (USD/MW)	85,783	95,903
FCR (%)	10.4	10.4
AEP (MWh)	776,136	776,136
CF (%)	44.3	44.3
LCOE (USD/MWh)	206.78	212.88

Table 15. The trend of the superconducting wire cost.

Years	2014	2019	Reduced Rate
Superconducting wire cost at 77 K	150 (USD/kA m)	83 (USD/kA m)	55.33%

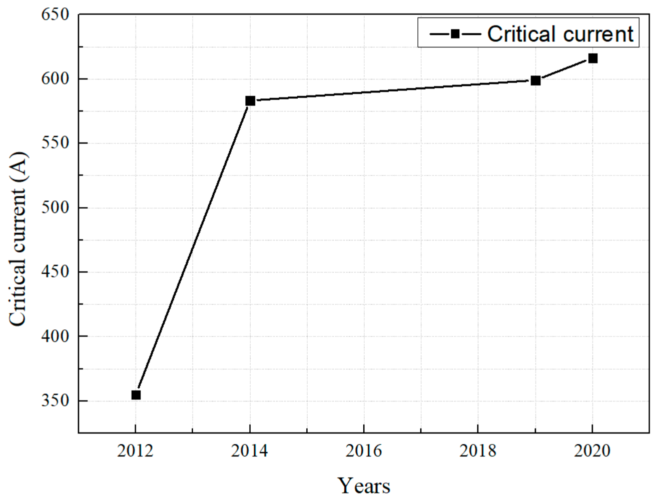

Figure 8. The critical current trend of the superconducting wire [44,45].

Table 16. The LCOE considering a 40% reduction in the superconducting wire cost of a 10 MW generator.

Items	PMSG Type FOWF	SCSG Type FOWF
Wind farm capacity (MW)	200	200
TCC (USD/MW)	1,403,490	1,721,544
BOS (USD/MW)	3,527,129	2,952,674
CAPEX (USD/MW)	6,687,259	6,511,897
OPEX (USD/MW)	85,783	95,903
FCR (%)	10.4	10.4
AEP (MWh)	776,136	776,136
CF (%)	44.3	44.3
LCOE (USD/MWh)	206.78	205.56

Economic feasibility evaluation reflecting the financial assumption was performed to confirm whether the PMSG type FOWF and the SCSG type FOWF can earn profits during the operation period. The financial assumptions for the evaluation of the economic feasibility were considered the domestic Renewable energy supply certification (REC) system. The REC weight was calculated considering the distance, which is over 15 km from the coast. The financial assumptions required for the economic feasibility study are shown in Table 17.

Table 17. The financial assumption for the evaluation of economic feasibility of the 200 MW class SCSG type FOWF.

Parameters	Value
SMP (USD/MWh)	80
REC (USD/MW)	48
REC weight	3.26
Loan rate (%)	70
Loan repayment period (year)	10
Loan interest (%)	2.5
Inflation rate (%)	1.45
Depreciation (year)	10
Corporation tax (%)	22
Discount rate (%)	4.5
Installation period (year)	3
Operation period (year)	25

The evaluation results of the economic feasibility are shown in Table 18. As a result of the evaluation of the economic feasibility reflecting financial assumption, Net Present Values (NPVs) of the PMSG and SCSG types FOWFs after tax were calculated as USD 607,455 and USD 468,810, respectively. Moreover, Internal Rate of Return (IRRs) of the PMSG and SCSG types FOWFs after tax were calculated as 5.98% and 5.34%, respectively. NPV of the PMSG type FOWF has a positive value from 15 years, and NPV of the SCSG type FOWF has a positive value from 16 years. Because the low operating cost of the PMSG type FOWF has caused NPV to reverse SCSG type FOWF from 10 years, the IRR of the PMSG type FOWF was higher than the SCSG type FOWF. It is worth investing in both FOWF projects because both IRR results are higher than the standard IRR of 4.5%.

Table 18. Evaluation results of economic feasibility of the 200 MW class PMSG and SCSG type FOWFs.

	PMSG Type FOWF			SCSG Type FOWF		
	1st Year	15th Year	25th Year	1st Year	16th Year	25th Year
AEP (MWh)	-	776,136	776,136	-	776,136	776,136
Energy price (USD/MWh)	-	252	291	-	229	241
Revenue (USD)	-	195,840	226,164	-	177,822	187,120
Operation cost (USD)	-	20,100	23,213	-	22,797	25,951
ICC (USD)	1,339,573	-	-	1,286,172	-	-
Loan balance (USD)	937,701	-	-	900,320	-	-
Loan interest (USD)	23,443	-	-	22,508	-	-
Loan payment (USD)	23,443	-	-	22,508	-	-
Corporate tax (USD)	-	250,374	289,141	-	263,779	296,890
After-tax cash flow (USD)	−23,443	137,077	158,302	-22,508	120,920	125,712
NPV (USD)	−960,134	3453	607,455	-921,859	37,504	468,810
IRR (%)	-	-	5.98	-	-	5.34

The LCOE calculation results of the PMSG type FOWF and the SCSG type FOWF were 206.78 (USD/MWh) and 212.88 (USD/MWh), respectively. According to calculation results, the PMSG and SCSG type FOWFs have a lower LCOE than that of Hywind Scotland wind farm in Scotland, UK operated by Hywind (Scotland) Limited, which has a range of 241.52~277.75 (USD/MWh) [46]. However, the LCOE of the SCSG type FOWF was still more expensive than that of the PMSG type FOWF. Looking at the trend of superconducting wire prices over the past five years, the price is falling rapidly. Considering the trend of the price decline, the LCOE of the SCSG type FOWF can reach 205.56 (USD/MWh) and the economic feasibility is expected within the next five years.

4. Conclusions

In this paper, the economic value of the PMSG and SCSG type FOWFs were analyzed and compared. The structure of the 10 MW class FOWT was designed through a joint research project in Korea. The platform for the 10 MW class FOWT was chosen as semi-submersible and expanded on the basis of the NREL floating concept. The PMSG and SCSG were compared in terms of weight, volume, operation, and cost to find the difference between the two generators applied to large wind turbines. In terms of weight, the SCSG type has been shown to be far more advantageous for the design of large wind farms. Because the SCSG is light, it is advantageous in terms of operation and maintenance but has the disadvantage of requiring additional consideration for maintenance of the cooling system.

To compare the two types of FOWF economically, the CAPEX and OPEX of a 10 MW class FOWT were calculated through a cost scaling equation. LCOE is calculated to compare the economics of the PMSG type FOWF and the SCSG type FOWF. As calculated, the SCSG type FOWF was 6.1 (USD/MWh) more expensive for LCOE than the PMSG type FOWF. When the cost of the superconducting wire of a 10 MW generator is reduced by 40%, the LCOE of the SCSG type FOWF is lowered by 1.2 (USD/MWh) than the PMSG type FOWF. In addition, during the operating period, we conducted an economic evaluation that reflects financial assumptions so that the PMSG type FOWF and the SCSG type FOWF can generate profits. After tax, the IRR calculation results for the PMSG type FOWF and the SCSG type FOWF were 5.98% and 5.34%, respectively. These results are higher than the standard IRR of 4.5%, confirming that it is worth investing in the 200 MW PMSG type FOWF project and SCSG type FOWF project with a 40% reduction in the cost of the superconducting wire. Considering the performance improvement and price decline of superconducting wires, the economic feasibility of the SCSG type FOWF is expected to be secured in the near future.

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Abbreviations

PMSG	Permanent magnet synchronous generator
SCSG	Superconducting synchronous generator
FOWT	Floating offshore wind turbine
FOWF	Floating offshore wind farm
LCOE	Levelized cost of energy
CAPEX	Capital expenditures
OPEX	Operating expenditures
FCR	Fixed charge rate
ICC	Initial capital cost
AEP	Annual energy production
AOE	Annual operating expenses
LLC	Land lease cost
O&M	Levelized operating and management cost
LRC	Levelized replacement/overhaul cost
TCC	Turbine capital cost
BOS	Balance of station cost
D_{WT}	Rotor diameter of wind turbine
C_{WT}	Capacity of the wind turbine
SMP	System marginal cost
REC	Renewable energy certificate

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