Review of Onshore and Offshore Wind Energy Systems: Technical Characteristics, Challenges, and Worldwide Prospects

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Abstract—**The global transition toward sustainable energy has intensified interest in wind power development, particularly in comparing the capabilities of onshore and offshore systems. This study provides a comprehensive assessment of the technical characteristics, energy potential, and operational challenges associated with both wind energy types worldwide. The analysis examines wind resource availability, turbine design features, power density, cost trends, environmental considerations, and grid-integration issues. This study compares OFWTs and ONWTs in terms of performance, design, environmental impact, and regulation. OFWTs, operating in stronger, steadier WSs (~9 m/s), achieve CFs above 50% and outputs up to 15 MW, as seen in Hywind Scotland's 56% performance. Despite scalability, they face higher energy costs (~$80/MWh) and marine ecosystem concerns. ONWTs, with lower WSs (~5–8 m/s) and 30–40% CFs, are more cost-effective (~$50/MWh) but present land-use and biodiversity challenges. Overall, site-specific strategies integrating floating and modular technologies are essential to balance efficiency, sustainability, and cost in future WE systems. The comparative evaluation highlights that optimizing future wind energy expansion requires a balanced approach: leveraging the maturity and cost-effectiveness of onshore systems while exploiting the superior resource quality and large-scale generation opportunities offered by offshore installations. The findings support policymakers and developers in selecting suitable wind strategies aligned with national energy goals and resource characteristics.**

***Keywords*—Environmental Impacts; Offshore Wind Turbines; Onshore Wind Turbines; Comparative Analysis; Capacity Factor Estimation.**

List of abbreviations

WSs: Wind speeds	ONWTs: Onshore wind turbines
WFs: Wind farms	OFWTs: Offshore wind turbines
RDs: Rotor diameters	MDs: Modular designs
WD: wake dynamics	DOE: Department of Energy
CFs: capacity factors	HAWTs: Horizontal axis WTs
PA: Pitch angle	ABP: Aerodynamic blade pitch
RE: renewable energy	CI: Cut-in
WP: Wind power	CO: Cut-out
WE: Wind energy	LCOE: Levelized cost of energy
PD: Power density	IC: Installed capacity
VAWTs: Vertical-axis WTs	EEZs: Exclusive Economic Zones
V: Voltage	I: Current
P: Power	AD: Air density
AT: Aerodynamic torque	SCs: Stator currents
	LCOE: Levelized costs of energy

I. Introduction

A. Motivations and Background

An essential component of environmentally friendly energy shifts, WE machines greatly lower greenhouse gases [1], [2]. As a highly advanced and commercially feasible RE generator, WP shines out for its potential to significantly contribute to improving WE safety and furthering decarbonization efforts. ONWTs and OFWTs are the two primary systems that must be carefully considered while implementing WTs. Both methods aim to generate electricity from WE, but they differ greatly in respect to structure, yield, ecological effects, and legal regulations [3], [4], [5]. The differences that have been found highlight the need for a comprehensive comparison study in order to improve WE budget optimization.

Because of their existing structures, affordability, and accessibility, ONWTs are widely used. They are usually placed in open spaces with mild to high WSs, which makes their setup and upkeep processes very simple. ONWTs are now a viable choice in many areas because of major improvements in their effectiveness and capacity brought about by scientific breakthroughs. ONWTs do, however, confront a number of difficulties. They involve a lack of available space, opposition from people because of worries about the effects on sight and sound, and variations in wind factors brought on by topography and obstacles such as forests and construction. These elements complicate plan viability and choosing a location, particularly in locations with high population densities [6], [7], [8].

During their end-of-life phase, WTs encounter a number of difficulties that eventually lead to their ultimate disposal. It is anticipated that over 60,000 WTs will have reached the end of their initial lifespan globally by 2030, with two-thirds of those being in the EU (see Fig. 1) [9], [10], [11]. The IC of WE are expected to rise from 540 GW in 2017 to 923 GW in 2022, representing a 70% growth over the 5-year period, based on the cumulative IC of RE sources between 2017 and 2022 shown in Fig. 2. Additionally, it is anticipated that in

2030, 2040, and 2050, the IC of WP would be 3101 GW, 6525 GW, and 8365 GW, respectively. Because of this, it can be predicted that in the upcoming years, WE will rank among the most significant RE sources worldwide [12], [13], [14].

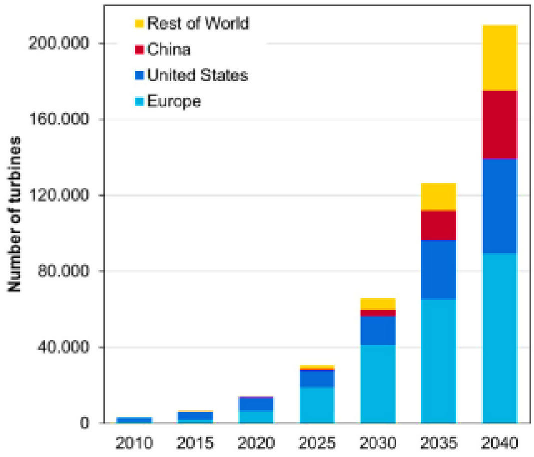


Fig. 1. Total WTs that would be at the end of their useful lives by 2040, broken down by global region [9]

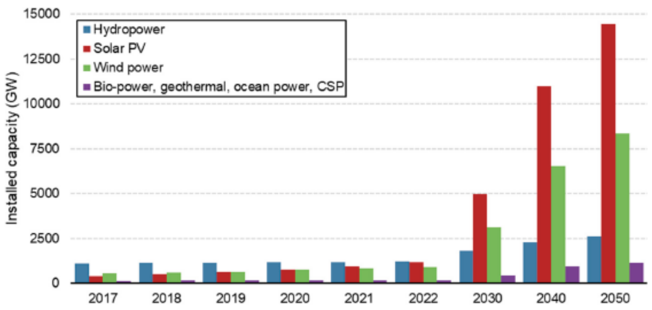


Fig. 2. The total IC of RE sources from 2017 to 2022 to reach net zero in 2030, 2040, and 2050

Over the open ocean, OFWTs benefit from greater, more reliable WSs, which raises the energy production per WT. Additionally, they eliminate the usage restrictions that ONWTs impose, enabling extensive expansion. Nevertheless, there are significant choices associated with these benefits. OFWTs must withstand challenging marine conditions, necessitating long-lasting, frequently costly components and layouts that can withstand adverse conditions, surf pressures, and saltwater damage [15], [16], [17]. Upkeep and fixes are harder and costlier due to the administrative challenges of reaching OFWTs' places. Notwithstanding these difficulties, OFWTs are a very attractive alternative because of their capacity and productivity, especially in areas with substantial power requirements and restricted site access [18], [19], [20].

One important factor to take into account is the effects that both ONWTs and OFWTs have on the surroundings. OFWTs may cause dispersion of habitat, endanger bat and bird species, and disturb regional ecology. Meanwhile, it's possible that OFWTs will affect aquariums by changing the cleanliness of water, patterns of travel, and surroundings. To handle these effects, a comprehensive evaluation of the natural world and application of green design principles is required. Furthermore, the way WE systems are implemented is greatly influenced by legislation. ONWTs must abide by environmental rules, negotiate neighborhood zoning rules, and participate in municipal procedures. On the other hand, OFWTs' ventures have to abide by stringent ecological standards, global agreements, and complicated marine rules [21], [22], [23].

Over 1000 GW of WE will be built worldwide by 2024, with ONWTs making up roughly 94% and OFWTs making up the rest, or 6% [24], [25], [26]. Leading nations in OFWTs include China and the UK, while onshore deployment is led by China, the USA, and Germany. Projects like Hornsea 2 in the UK have 1.3 GW from more than 150 WTs; however, OFWT arrays normally range from 50 MW to over 1 GW. In relation to regional electricity supply and access to land, ONWTs-farms can range from 10 to 100 WTs per site. By 2035, OFWTs production is expected to surpass 380 GW, thanks to developments in variable vessels and advantageous maritime regulations. Assessing the technical, physical, and financial contexts in which WT arrangements function requires taking these installation indicators into account [27], [28], [29], [30].

By methodically combining computational performance prediction with an evaluation of ONWTs and OFWTs, this research makes an innovative approach. Prior research frequently looks at these structures independently or concentrates solely on capability or price. On the other hand, this work combines installation with Simulink-created electricity. Information, design specifications, and evaluations of the effects on the surroundings. This combined strategy fills a known break in the past by enabling an increased and useful structure for assessing installation options, which frequently ignores whole-system performance metrics in local situations [31], [32].

B. Literature Review

Making the transition to RE is essential to combating global warming, and WE have emerged as a leading option. Both ONWTs and OFWTs have unique advantages and challenges in terms of effectiveness, structure, ecological effects, and regulation. The article provides a comprehensive analysis of these structures by synthesizing the findings of the existing literature. Efficacy is the primary criterion to assess WE systems. OFWTs can frequently produce more power than ONWTs because of greater and more constant WSs across wide oceans. Refs. [33], [34] discovered that OFWTs may achieve ratings above 50%, as opposed to 35–40% for ONWTs. This effectiveness benefit is a result of decreased instability and impediments in maritime environments [35], [36].

However, OFWTs are more expensive to operate and maintain. In [15], OFWTs require special boats and skilled labor for construction and maintenance, which is frequently counterbalanced by their greater generation of electricity. ONWTs, which benefit from quicker access and lower administrative expenses, are less costly in locations with sufficient wind potential. The balance between cost-effectiveness and recital remains a key consideration for builders. Because of the severe seafloor and restricted access, maintaining OFWTs presents special difficulties. In order to boost repairs and minimize outages, Ref. [37] highlighted an opportunistic care technique that assesses mobility. The researchers suggest methods for choosing WT constraints utilizing sophisticated simulation tools. Since ONWTs operate at lower WSs (5 to 8 m/s), rigorous terrain study is necessary to minimize disturbance and maximize WE extraction. This difference highlights the OFWTs' scaling benefit over the ONWTs' ease of logistics. The development of WP from its first use in mills to contemporary huge WFs is traced in the historical review in [38]. The paper describes how developments in technology have increased the ability, reliability, and productivity of WTs for both ONWTs and OFWTs. Huge RDs and movable bases are two innovations that have made OFWTs possible. With an extended period of running, ONWTs have seen substantial advancements in sound mitigation and adaptability. The complementary functions of ONWTs and OFWTs in accomplishing WE variety and climate change mitigation are highlighted by this past view. According to [23], MDs are used in current ONWTs to accommodate different physical situations. Additionally, concepts like quieting processes and straightforward architecture intended to lessen public outrage are also affected by the optical and hearing impacts caused by WTs.

The effects of WTs on the planet are a major area of study. In their comparison study of Alberta's WE infrastructure, Ref. [39] shows that WP and other RE supplies can cut emissions by up to 98.5% when contrasted with oil and gas. This emphasizes how important WE are to attaining energy independence and carbon neutrality. Every fish travels to the bottom substrates, and aquatic fauna may be impacted by OFWTs that disturb aquariums. Refs. [40], [41], [42], [43], [44] emphasized the importance of doing thorough ecological influence evaluations before constructing OFWTs. Environmental impacts can be reduced by moving WTs to fewer hazardous areas and utilizing surveillance equipment. The two main ecological matters that ONWTs face are avian fatalities and division of habitat. A combination of (DG-WT-PV may provide power at an equal cost of $0.432/kWh, while also lowering CO2 pollutants and guaranteeing a dependable electricity source for a distant, oil-reliant area, according to research conducted on the island of Mahtab [45], [46], [47].

To reduce accidents with birds, Ref. [48] emphasized the importance of tactical placement and the use of advanced radars. Regulations have a significant impact on how WE schemes are implemented. OFWTs are subject to complex legal environments, such as global agreements and shipping rules. According to the U.S. DOE, permitting OFWTs can occasionally cause implementation delays due to the lengthy approval processes and numerous stakeholders involved. ONWTs undergo fewer legal hurdles, but they still have to deal with public objections, acquisition issues, and municipal zoning laws [49]. Refs. [50], [51], [52], [53] assert that efficient regulations and meaningful public engagement are essential to the successful deployment of ONWTs. Explicit and encouraging guidelines are needed in both realms to achieve long-term prosperity.

Tests comparing ONWTs and OFWTs can reveal that cost is a decisive factor. ONWTs are typically less expensive as they need fewer setups and upkeep. Despite having a greater latent for electricity, OFWTs come with substantial startup and operating expenses. Ref. [12] revealed that the LCOE for OFWTs remains greater than that of ONWTs, despite progress in technology decreasing it. Nonetheless, OFWTs are increasingly seen as a viable option for regions with high WE consumption or restricted land access. Ref. [54] pointed out that OFWTs are attractive for crowded coastal locations. These compromises guarantee that ventures in WE balance regional needs and available resources. The social factors of WE play a major role in its acceptance. ONWTs may encounter opposition from neighboring towns. Ref. [55] emphasizes that early input from stakeholders in the scheduling phase may aid in problem-solving and increase the public's trust. OFWTs may encounter resistance from further oceanic workers, such as fishing towns, despite being less visually disruptive. According to [40], involving these parties in determining issues reduces conflict and encourages creative solutions. Technological development continues to influence the prospects of WE. OFWTs are becoming more viable and less expensive thanks to advancements in self-repairing and solar WT knowledge. An ongoing unruly for ONWTs is being resolved by advancements in sound diminishing and WT efficacy. Ref. [56] noted that mixing PV and WE would be eco-friendly and increase energy consistency. These advancements point to a future where WE schemes will be more effective, mainstream, and globally friendly.

The literature highlights a number of aspects of WE installation, such as layout, efficacy, approval from society, subjects apply to the and governing frameworks [27], [57], [58], [59], [60], [61]. OFWTs are more mountable and produce more WE, but they expense more and have a greater eco-friendly influence. ONWTs are more readily available and less expensive, but they have land-dwelling usage matters and are less effectual. A fair evaluation of these factors is necessary to maximize WE funds and advance global RE goals. The significance of WD in various climatic circumstances is highlighted by recent developments in WT. An extensive investigation on HAWT functioning under temperature stratification was carried out [62]. Their results show how WD and, in turn, WT recital are affected by heat stratum. This knowledge is essential for placing WTs as efficiently as possible, especially in big WFs where WD can drastically lower energy production. Making changes to the design is also essential for enhancing the WT act. A new method using guide rings to improve the aerodynamic efficiency of HAWTs was presented [63]. Their study demonstrates how this layout lowers skeletal stress and improves harvesting yield, which may prolong the WT's lives. These developments highlight how the WT strategy is always changing to maximize WE harvest while lowering operating prices. An additional novel tendency is the integration of hybrid technologies into RE schemes. In order to develop a hybrid scheme, Ref. [64] suggested putting PV panels atop WTs. The benefits of PV and WE are combined in this integration, demonstrating that this strategy can increase grid stability, representing a breakthrough in RE keys.The highlight gaps in prior research:

- Most studies focus on either technical performance or economics/environment, but rarely combine all.
- Comparative global studies of OFWTs vs ONWTs with real datasets are scarce.

- Environmental and regulatory considerations are often underrepresented in performance analyses.

C. Contributions

Unlike prior studies, this paper systematically compares ONWTs and OFWTs' potential using both empirical wind datasets and simulation outputs, while integrating cost, capacity factor, and environmental impact for actionable insights. With an emphasis on important elements like efficacy, layout thoughts, ecological effects, regulations, and financial viability, this work provides an in-depth comparison of OFWTs and ONWTs. This investigation offers a comprehensive viewpoint that combines quantitative data with qualitative analysis. This work is so long as helpful information for maximizing WE funds, in contrast to earlier research that frequently looks at them separately. The discovery of OFWT's benefits, including CFs above 50% and the bulk to produce up to 15 MW per WT, is one of its chief donations. Contests like increased setting up prices and conservation pressures on maritime bionetworks are covered in this work. In the same way, the study addresses issues including biological consequences and disputes over terrestrial usage while highlighting ONWT's financial potential with a lesser LCOE of \$50/MWh. The report offers location-precise campaigns to optimize WE yields and negotiate intricate supervisory environments after conducting a thorough investigation. By combining ecological and rule aspects with WE yield and bulk measures, it also presents new results that aid in the decision-making of developers, technologists, and congresspersons. In order to ensure a detergent and sustainable RE upcoming, the study concludes by offering a useful basis for promoting the use of the WE scheme. The information used here came from a mixture of available works and globally accessible information. WS shapes were extrapolated from areas such as ONWTs America and OFWTs EU. In important marketplaces, these locations are representative of high-potential WP regions. The IRENA's combined results from different sites are the basis for LCOE values (\$80/MWh for OFWTs and \$50/MWh for ONWTs). While ONWTs values (30–40%) are based on operational data from WFs, OFWTs CFs (over 50%) [65], [66], [67].

II. System Structure

In this research, OFWTs and ONWTs are compared in real scenarios. With an emphasis on typical regions with significant potential for OFWTs and ONWTs, WS and PD information were collected from a number of widely accessible databases and prevailing works. These datasets capture the spatial and temporal variability inherent in WE resources by offering detailed WS profiles at several heights (10 m, 40 m, and 80 m). MATLAB/Simulink is used here. ONWT (P= 3–5 MW, RD =100 m, hub altitude = 80–110 m) and OFWT (P= 10–15 MW, RD =150 m, hub altitude 80–110 m) are the model's WT characteristics. In order to model the machine and ABP modifications at varying WSs, outside working factors such as rotational speed and a static PA of 35.5° were employed as regulator inputs. WS data and WT shape are used to calculate torque. As a result, mechanical power is converted into electrical outputs. Furthermore, by including WT (CI-WS= 3 m/s) and cut-out (CO-WS= 25 m/s), the model imposes accurate operating restrictions. This technique offers a strong foundation for comparing the yield stability, control receptiveness, and efficiency of OFWTs and ONWTs. The schematic diagram for ONWTs and OFWTs is displayed in Fig. 3 and Fig. 4, respectively [68], [69]. Although onshore WTs may use staggered engines for cost-effectiveness, OFWTs often use straight-drive units to minimize upkeep in difficult situations. ONWTs frequently contain armored concrete, while OFWTs can be floating stages made to resist seawater weathering.

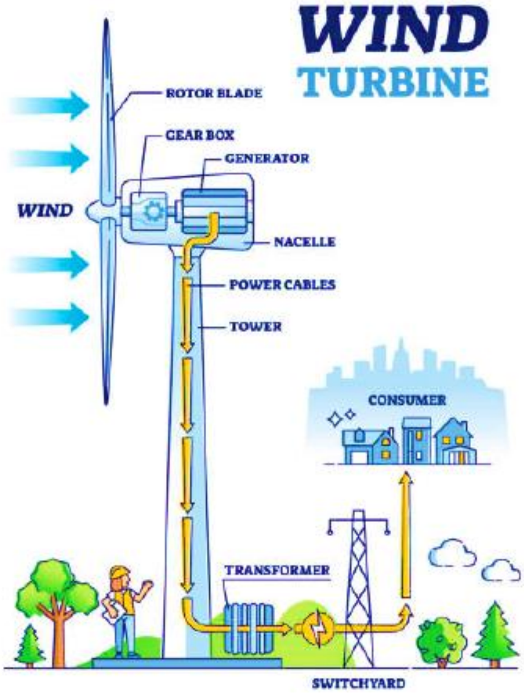


Fig. 3. ONWTs system [70]

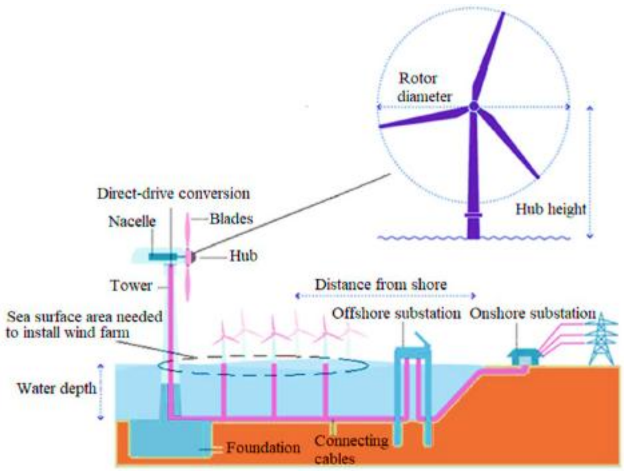


Fig. 4. OFWTs system [70]

III. A Comparison between ONWTs and OFWTs

Two WTs models are combined in Fig. 5 to illustrate ONWTs and OFWTs applications, correspondingly. Utilizing a customized MATLAB software, a variety of CFs are assigned to compute local yields. A range of estimated yearly generated electricity values is then sequentially computed in relation to the respective CFs. Additionally, comparisons between the ONWTs and OFWTs situations can be made thanks to the generated data. This facilitates the development of a more thorough analysis when assessing viability and efficacy on an individual basis [69].

Because of their different operating objectives and atmospheres, OFWTs and ONWTs are fundamentally different. Sturdy buildings are necessary to withstand maritime stresses since OFWTs are designed to capture greater, more reliable WSs. Conversely, ONWTs are made to maximize both logistical viability and affordability. Because of the increased disturbance and decreased WSs they encounter, smaller layouts and a precise choice of location are required. OFWTs may produce > 10 MW each and are larger, with RD >220 m. Cutting-edge OFWT technology is designed to improve the WE production from the tremendous WSs. The bases of OFWTs are determined by seabed features and the sea depth. Basics of OFWTs in sea up to 30 or 60, or 100 meters, and so are costly. These bases are done to enable OFWTs to run safely. Drone-based checks, advanced tracking systems, robotic maintenance equipment, and mixed and covered steel materials are required for this [71], [72]. ONWTs have RD < 150 m and operate between (1.5 – 5) MW. The landscape has a significant impact on the WT's direction and position. Large items like blades and nacelles must be delivered by road or train to far hilly regions. ONWTs address concerns about disruptive noise and visible invasion by using softer blade layouts and shorter towers. Advanced aerodynamic profiles reduce operating noise levels [73].

Research shows that ONWTs can have an impact on bat and bird numbers. In addition, OFWTs have an adverse impact on marine mammals [74]. Careful site selection and improved WT-ABP design are important things to reduce collision risks. The recent projects rely on environmental assessments that include biodiversity monitoring and underwater noise investigations [75]. Regulations have a major role in controlling the setup of WTs. ONWTs are subject to strict zoning, land use, and environmental impact regulations. Policies may require developers to address public concerns about noise, sight disturbance, and shadow flickering. In some of the pioneer countries, strict zoning regulations ensure that WFs are situated far from populous areas and important ecological zones. On the other hand, OFWTs comply with complex marine regulations that involve a number of stakeholders, such as environmental agencies and government officials. EEZs regulate the installation of WTs, although environmental impact assessments are necessary to obtain licenses [76].

Notwithstanding high initial costs, Hywind LNG Scotland achieved an impressive CF of 56% in its first year, surpassing the typical onshore CF of 30% to 40% [77]. WTs are characterized by their position, dimension, and axis direction. ONWTs are frequently slighter than OFWTs due to practical factors like setup and shipping. HAWTs dominate both the ONWTs and OFWTs industries because of their high capacity and effectiveness. Though less common, VAWTs are becoming more popular for use in small cities [78].

OFWTs are more profitable than their ONWTs counterparts because of their larger WTs and more consistent WSs. OFWTs frequently have CFs > 50%, while ONWTs typically have CFs from 30 – 40%. However, increased efficacy comes at a higher cost. OFWTs installations require expensive structures, specific construction boats, and increased servicing due to the challenging seafloor [9]. ONWTs are less effective yet more affordable, but they have fewer complex foundations and easier maintenance access. ONWT and OFWT have an LCOE of $50 and $80 per MWh, respectively, according to IRENA. However, ongoing technology advancements, such as larger turbines and movable bases, are reducing the gap in cost between them. Both OFWTs and ONWTs present unique challenges. The majority of the public's objections to ONWTs from vibration, light flicker, and perceived effects. Land scarcity and competition with agriculture are further factors limiting the expansion of ONWTs [79], [80]. OFWTs' initiatives pose administrative and technical obstacles despite being exempt from a lot of them. It is costly and challenging to set up and upkeep WTs in remote oceans. Furthermore, because OFWTs require undersea systems and connections to transmit power to the ground, grid-linked remains challenging [81]. On the basis of important operating and engineering factors, Table I compares OFWTs and ONWTs. OFWTs produce more electricity (10–15 MW for each WT) due to their greater WSs (about 9 m/s) and CFs (>50%) [82]. ONWTs, on the other hand, can achieve CFs of 30–40% and yields of 2–4 MW for each WT while operating at less WSs (about 5–8 m/s). This table analysis highlights the trade-offs between price, adaptability, and efficacy and offers insights for local implementation strategies in wind energy plants [12], [83], [84].

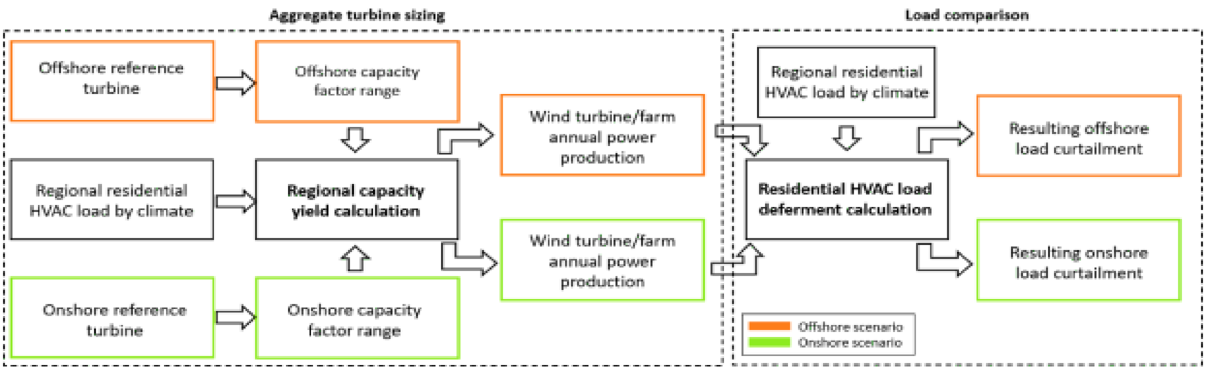


Fig. 5. An illustration of the methods used to create WE systems and estimate the WP output that results [69]

TABLE I. COMPARISONS OF THE DESIGN AND FUNCTIONING FEATURES OF OFWTS AND ONWTS

Item	ONWTs	OFWTs
WS	~5–8 m/s	~9 m/s
CF	30-40 %	>50 %
WE output	2-4 MW	10-15 MW
WT size	~100 m	~ 150 m
Generated voltage (V)	39.5 at 8.2 m/s	123 at 9.7 m/s
Generated power (W)	1.9 at 8.2 m/s	6 at 9.7 m/s
LCOE	~$50/MWh	~$80/MWh
Turbulence influence	Variance is caused by geography and impediments; turbulence is fewer than OFWTs.	In optimum erratic designs, the strength of turbulence can increase by up to 20%, increasing construction damage.
Seasonal disparity	More seasonal variation necessitates meticulous tuning and monitoring	Little fluctuation, increased production all year long
Topographical tests	Variance is caused by topography and impediments; cautious choosing of a location is necessary.	Submerged bases and cutting-edge materials are needed to support maritime troops.
Nearness to the request	Often found in isolated or suburban areas, requiring a strong electrical supply.	Lowering transmitting losses, frequently close to metropolitan beaches
Price	Lower compared to OFWTs	Higher compared to ONWTs
Scalability	Restricted by consensus and accessible land	Highly because of reliable winds and bigger WTs

IV. RESULTS AND DISCUSSIONS

According to studies, average WSs for ONWTs range from 5 to 8 m/s, but they can exceed 9 m/s at OFWTs positions [85]. For those in good positions, the CFs of ONWTs surpass 45% and reach 30% to 40% of OFWTs. ONWTs have rated power between 2 MW and 4 MW, while OFWTs have rated power between 10 MW and 15 MW [15], [86].

A comparison of monthly WS changes for both ONWTs and OFWTs, recorded at 3 distinct heights (10, 40, and 80 meters), is shown in Fig. 6, which was produced using our specially designed built-house Python program. The software was created especially to handle periodic WS data and display it. The investigation highlights significant variations in the seasons and WS patterns, both of which are critical for the growth of WE. WSs at 10 m height at OFWTs areas start at 8 m/s in Jan, grasp a high point of 8.9 m/s in Aug., and then drop to 8.1 m/s by Dec. OFWTs-WSs are constantly higher above 80 meters, peaking at 9.7 meters per second in Aug after beginning at 9 meters per second in Jan. The lack of obstacles like trees or buildings at OFWTs locations is thought to be the cause of these higher WSs since it permits more even and steady wind flow across the open sea. OFWT sites are especially advantageous for WE generation due to the steady patterns throughout the months, with turbines benefiting from larger CFs.

The monthly fluctuation in WE-PD (W/m2) for ONWTs and OFWTs sites at the mentioned three heights is depicted in Fig. 7. In Jan, the OFWT-PD at 40 m is 350 W/m2, peaks in Aug at 385 W/m2, and then falls back to 350 W/m2 in Dec. OFWT-PD is much higher at 80 m, peaking at 465 W/m2 in Aug and falling back to 405 W/m2 in Dec, from 400 W/m2 in Jan. At 10 m, 40 m, and 80 m, the average OFWT-WS is 6–8 m/s, 8–10 m/s, and 10–12 m/s, respectively. At the same heights, OFWT-WS are often lower, ranging from 4 to 6 m/s, 6 to 8 m/s, and 8 to 10 m/s. Information on WS and PD used here came from a variety of sources, including available articles, worldwide datasets, and conventional analytical models. Representative mean WSs were taken from published site-specific research and modified to account for realistic variability using Weibull distributions. By following the guidelines in [88], [89], this method guarantees that the values obtained are in line with industry-standard evaluations of wind resources.

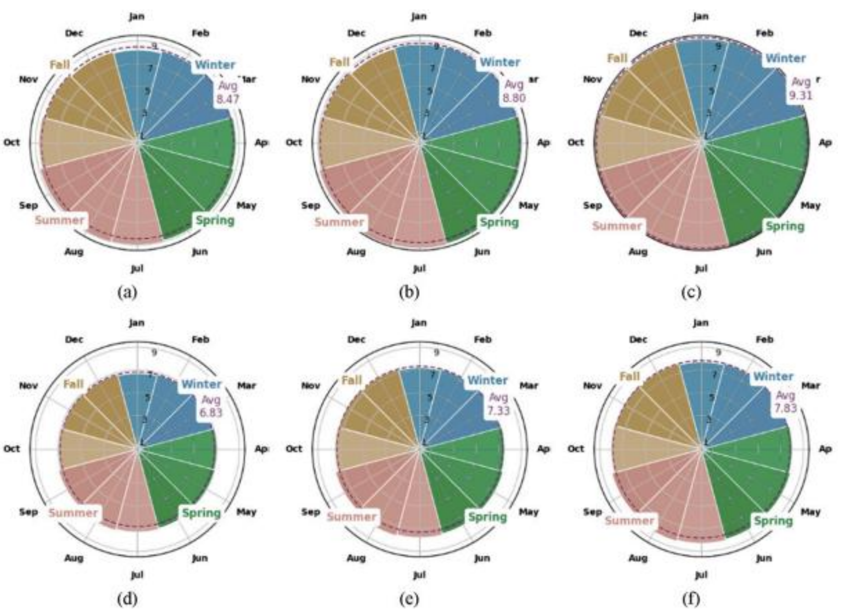


Fig. 6. Once-a-month WS patterns for ONWTs (lower row) and OFWTs (upper row) at various elevations (a, d) 10 m, (b, e) 40 m, and (c, f) 80 m [87]

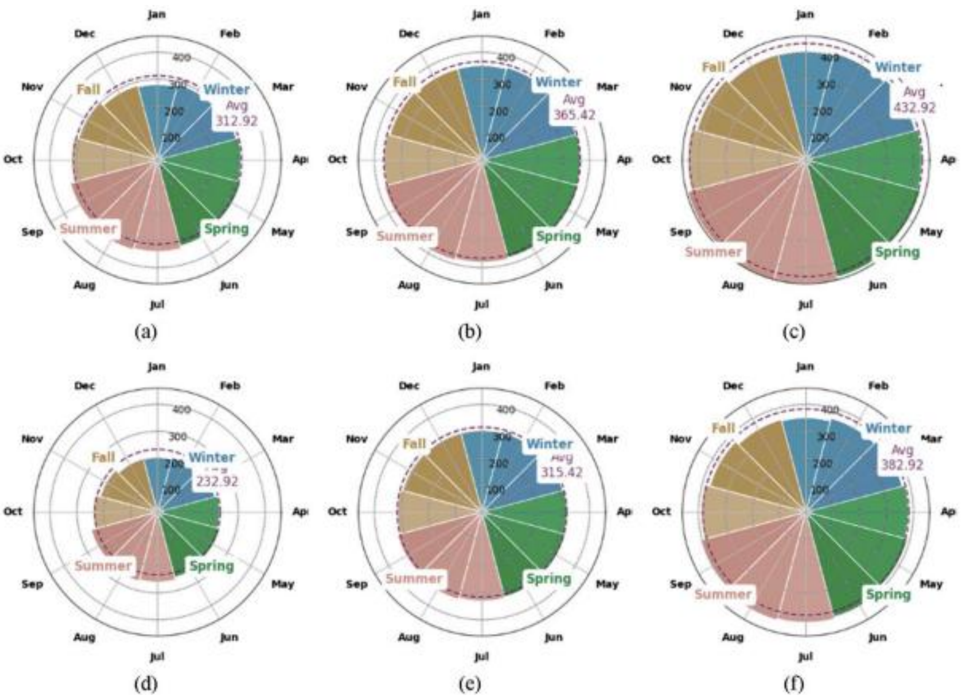


Fig. 7. Once-a-month WS- PD patterns for ONWTs (lower row) and OFWTs (upper row) at various elevations (a, d) 10 m, (b, e) 40 m, and (c, f) 80 m [87]

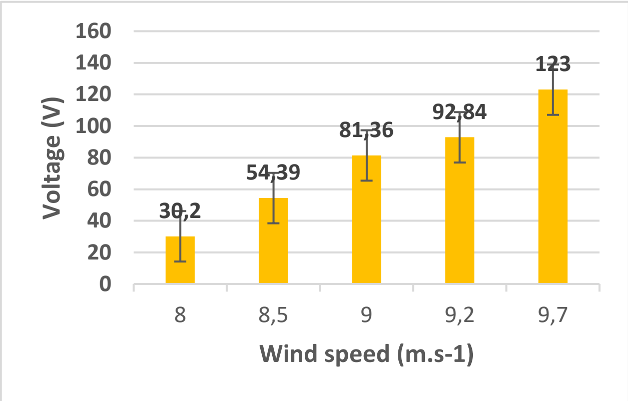
For both places, there is a noticeable difference in WS between the two heights. The OFWT-WS is about 1 m/s faster at 80 m than it is at 10 m. Seasonally, during the summer (Jun–Aug), both ONWT and OFWT-WS exhibit greater values, peaking in Jul and Aug. WSs are lower throughout the winter months of Dec through Feb. These fluctuations show that additional storage units or grid incorporation are required to handle times when WSs are lower. In conclusion, the figure shows how OFWT areas offer a distinct advantage for the development of WE because of their greater and more reliable WSs. Higher WE output and efficacy are guaranteed by OFWT's ability to capture heavier WSs, particularly at 80 meters. Even though ONWTs are more affordable and available, they still confront difficulties due to shallow coarseness and fewer WSs, which necessitate careful spot choice and WT positioning. When ONWTs and OFWTs are involved, the investigation emphasizes the significance of tallness optimization and periodic wind outlining.

A MATLAB/Simulink prototype created to mimic the WE system was used to create the (V\ I \ P) output data shown in Fig. 8 – Fig. 10. A typical WT with the next characteristics was utilized: hub tallness of 80–110 m, RDs of roughly 100 m (ONWT) and 150 m (OFWT), and 3–5 MW valued P (ONWT) and 10–15 MW valued P (OFWT). In order to represent normal ONWT and OFWT average conditions, the WS input varied between (6.5 m/s – 9.7 m/s). 1.225 kg/m3 was chosen as the AD. With CI and CO -WSs set at 3 m/s and 25 m/s, accordingly, a fixed PA of 35.5° was employed. The simulation used a simple machine block to transfer mechanical power to an electrical output after calculating AT based on WS input and WT characteristics. While I and P outputs took load factors to heart, V was expressed as related to the speed of rotation and flux association. In order to facilitate a comparative study, these characteristics and presumptions guarantee that the simulations accurately reflect typical operating reactions for both ONWTs and OFWTs.

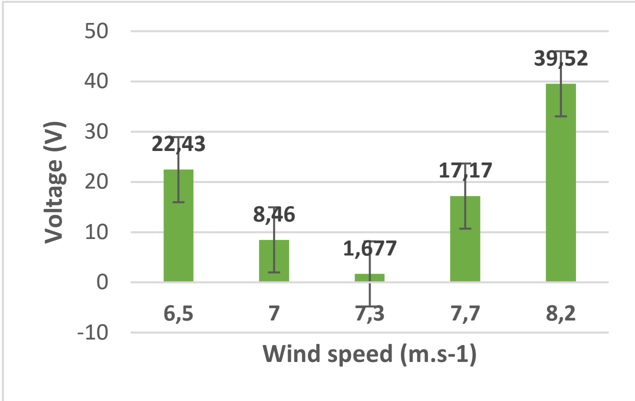
Under different WSs, Fig. 8 contrasts the V output of ONWTs and OFWTs. From 30.2 V at 8 m/s to a peak of 123 V at 9.7 m/s, the OFWTs-V increases gradually with WS in Fig. 8(a). On the other hand, Fig. 8(b) demonstrates that ONWTs produce Vs that are lower and more variable, beginning at 22.43 V at 6.5 m/s, decreasing to 1.68 V at 7.3 m/s, and then increasing to 39.52 V at 8.2 m/s. In comparison to their onshore equivalents, OFWTs generally function at higher and more consistent Vs. The V data shown in Fig. 8 came from MATLAB simulations that included environmental parameters, WT characteristics, and WS profiles for both scenarios.

Simulation findings of I output for ONWTs and OFWTs, taking into account WT design characteristics and fluctuations in WS, are shown in Fig. 9. Fig. 9(a) illustrates how the I flowing through OFWTs increases steadily as WS increases, from 0.01199 A at 8 m/s to 0.04883 A at 9.7 m/s. ONWTs, on the other hand, produce smaller and less consistent currents, ranging from 0.008904 A at 6.5 m/s to 0.01569 A at 8.2 m/s, as seen in Fig. 9(b). As WS increases, OFWTs often produce more I in a more constant manner than ONWTs.

WT- P output and WS are contrasted in Fig. 10 for both ONWTs and OFWTs. OFWTs in Fig. 10(a) exhibit a dramatic rise in power with WS, peaking at 6.0061 W at 9.7 m/s after reaching 0.3621 W at 8 m/s. ONWTs, on the other hand, produce less, ranging from 0.2694 W at 6.5 m/s to 1.9298 W at 8.2 m/s, as seen in Fig. 10(b). In general, when WS increases, OFWTs produce more power more consistently. MATLAB simulations that included WS profiles and WT characteristics for both environments produced the P values shown in Fig. 10.

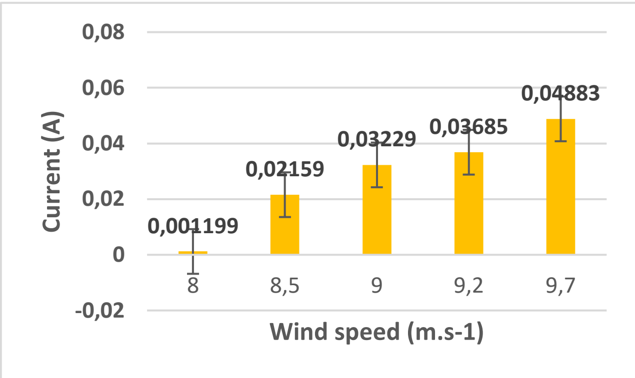


(a) OFWT

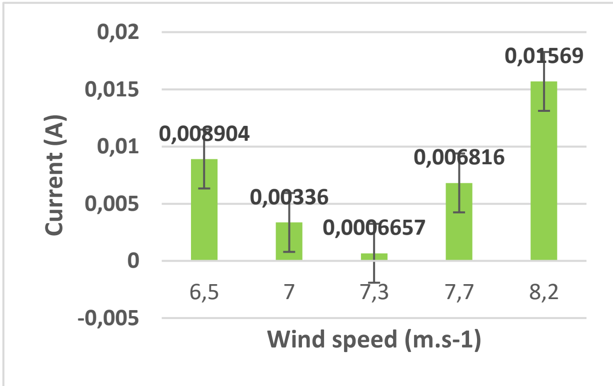


(b) ONWT

Fig. 8. The relationship within WS and V: (a) OFWTs, and (b) ONWTs

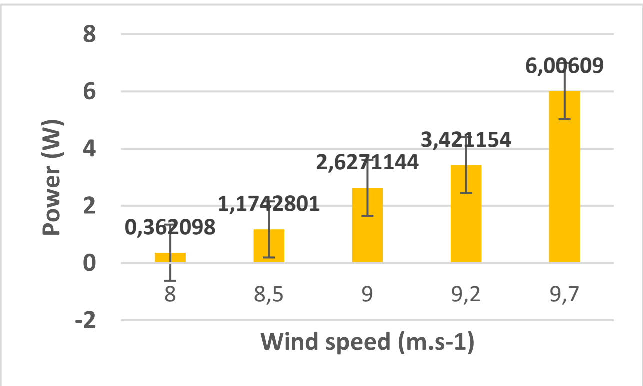


(a) OFWT

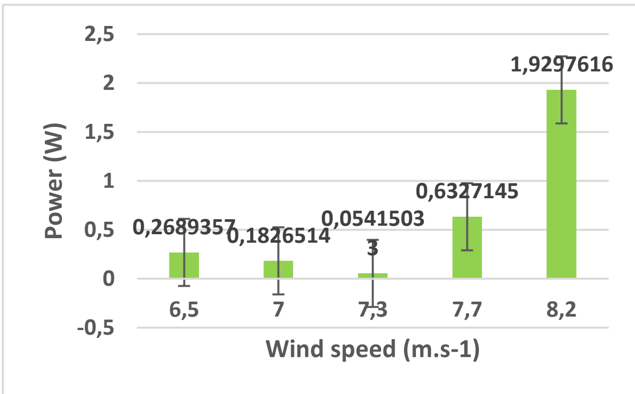


(c) ONWT

Fig. 9. The relationship within WS and I: (a) OFWTs, and (b) ONWTs



(a) OFWT



(b) ONWT

Fig. 10. The relationship within WS and P: (a) OFWTs, and (b) ONWTs.

Fig. 8 – Fig. 10 present the V, I, and P output data that were derived from the model that simulates the electric act of WTs. ONWTs (3–5 MW, 100 m rotor, 80–110 m hub) and OFWTs (10–15 MW, 150 m rotor) are included in the model. At sea level, the AD is 1.225 kg/m³, and WSs range from 6.5 m/s to 9.7 m/s. CI and CO-WSs were set at 3 m/s and 25 m/s, respectively, with a constant 35.5° PA. WS input and WT parameters were used to calculate AT, and a simpler machine block was used to transform mechanical power into electrical output. I and P outputs represented load characteristics, whereas V was characterized as proportional to rotational speed and flux linkage. These assumptions provide an accurate simulation of typical ONWTs and OFWTs reactions for comparative study. In addition, Table II and Table 3 summarize the outcomes from OFWTs and ONWTs, respectively [87].

TABLE II. OFWTs OUTPUTS (V\I\P) UNDER DIFFERENT WS VALUES

Wind speed	OFWT outputs		
	V	I	P
8 m. s^{-1}	30.2 V	0.001199 A	0.362098 W
8.5 m. s^{-1}	54.39 V	0.02159 A	1.17428 W
9 m. s^{-1}	81.36 V	0.03229 A	2.627114 W
9.2 m. s^{-1}	92.84 V	0.03685 A	3.421154 W
9.7 m. s^{-1}	123 V	0.04883 A	6.00609 W

TABLE III. ONWTs OUTPUTS (V\I\P) UNDER DIFFERENT WS VALUES

Wind speed	ONWT outputs		
	V	I	P
6.5 m. s^{-1}	22.43 V	0.008904 A	0.268936 W
7 m. s^{-1}	8.46 V	0.00336 A	0.182651 W
7.3 m. s^{-1}	1.677 V	0.0006657 A	0.05415 W
7.7 m. s^{-1}	17.17 V	0.006816 A	0.632715 W
8.2 m. s^{-1}	39.52 V	0.01569 A	1.929762 W

SCs at WSs of 9.7 m/s and 8.2 m/s with a fixed PA of 35.5° are compared in Fig. 11. The SCs exhibit higher-amplitude sinusoidal waveforms at 9.7 m/s (Fig. 11(a)), suggesting higher WP generation as a result of increased kinetic WE. At 8.2 m/s (Fig. 11(b)), on the other hand, the SCs have a similar form but have smaller amplitudes, indicating less WP generation. This demonstrates that greater WSs result in larger SCs, which is in line with the link between WE and WT performance. Because of the fixed PA, SCs variations are guaranteed to be caused exclusively by changes in WS. OFWTs typically produce smoother and higher SCs under similar WS conditions due to more stable and stronger OFWTs, albeit this is not shown.

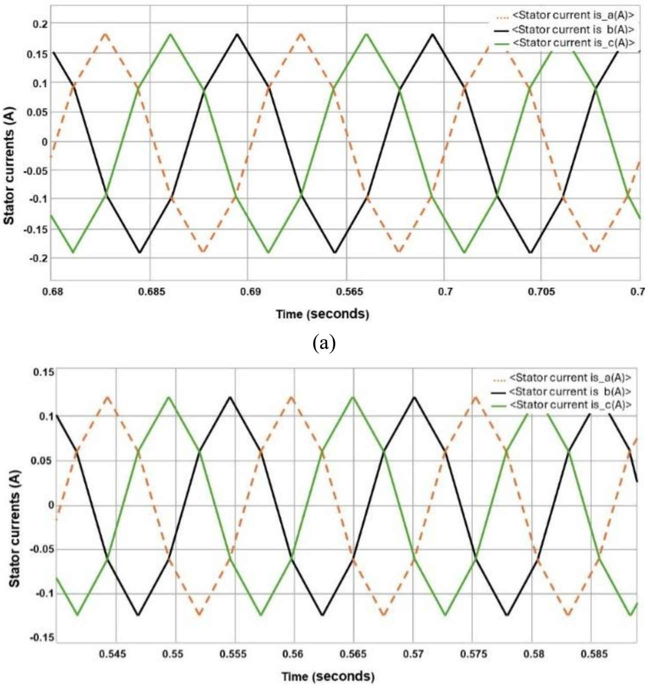


Fig. 11. Evaluation of SCs at finest PA: (a) OFWT, and (b) ONWT

V. DISCUSSIONS

The comparison of OFWTs and ONWTs reveals unique features, benefits, and difficulties for each system. Although ONWTs are a well-established and reasonably priced technology, they have drawbacks such as land use conflicts, noise and visual pollution, and a shortage of available sites. They also provide inexpensive installation and maintenance costs and quick returns on investment. Although OFWTs have larger CFs, stronger, more reliable winds, and less of an aesthetic impact, they are expensive to install and maintain, present technological difficulties in deep waters, and may endanger marine habitats [90]. Economically speaking, OFWT projects require sophisticated designs and specialized infrastructure, which leads to LCOE. However, advancements in floating platforms, in particular, are lowering these costs and allowing for deeper-water deployment. Global capacity is now dominated by ONWT systems (around 95%), but by 2050, the balance may change due to advancements in offshore technologies. ONWTs encounter opposition from the public because of their noise and effects on local wildlife, while OFWT facilities have the potential to disrupt marine life through electromagnetic effects and noise. Therefore, to make sure both systems are in line with sustainability goals, site-specific designs and ongoing effect evaluations are still crucial [70].

VI. CONCLUSIONS

This investigation compares the performance of OFWTs and ONWTs using literature-based performance analysis and integrated simulations. Simulink simulations confirmed smoother V and P profiles, and OFWTs (10–15 MW, >150 m rotor, >100 m hub height) demonstrated greater CFs (≥50%) as a result of more consistent wind conditions. Due to land-induced turbulence, ONWTs (3–5 MW, ~100 m rotor) showed higher output variability and lower CFs (30–40%). OFWTs offer superior scalability for coastal demand, even if ONWTs achieved a lower LCOE (~$50/MWh) than OFWTs (~$80/MWh). Although OFWTs deployment lessens land-use disputes, it may have an impact on marine ecosystems. Overall, the findings show trade-offs between cost, environmental effect, and efficiency, highlighting the fact that site characteristics, grid capacity, and sustainability concerns all influence the best deployment. Analytical dependability was improved by combining simulation and empirical data, and future studies will focus on wake analysis, dynamic grid modeling, and hybrid wind optimization to help guide investment and policy choices.

Declarations

Author Contribution: All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

Sustainable Development Goals: Sustainable Development Goals mapped to this document, Affordable and Clean Energy Goal 7.

Data Availability: The data used to support the findings of this study are available at reasonable request from the corresponding author.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

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