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Design Optimization and Assessment of Floating Solar PV with Wind Turbine Systems at KEPZ

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***Abstract*—Renewable energy holds enormous potential in Bangladesh, but significant obstacles must be overcome to fully harness its benefits. With natural gas being the primary source of power generation in the country, there is a growing need to explore alternative sources of energy to reduce emissions and relieve the pressure on limited fuel supplies. Wind turbines (WT) and solar photovoltaic (PV) systems are currently being deployed to harness renewable energy, and Bangladesh's unique geographical features, including being a riverine country with a modest land area, make it an ideal candidate for floating PV and WT installations. However, the intermittency of renewable generation and high upfront costs pose significant challenges to the technical and economic feasibility of microgrid operation. The use of Energy Management Systems (EMS) and Grey Wolf Optimization (GWO) can help optimize the use of renewable resources and minimize capital costs, respectively. In this research, a methodology is proposed to assess the economic feasibility of floating PV and WT in the Korean Export Processing Zone (KEPZ), a critical hub of the country's economic activity, while minimizing renewable energy costs using the GWO technique. Mathematical models are used to design the hybrid renewable system, and load-demand data is collected from KEPZ. Based on hourly resource data, annual hourly floating PV and WT energy generation is estimated, and the electricity cost (LCEO) is evaluated, yielding a cost of 0.099$/kWh for the system, taking into account project lifetime, interest rate, and inflation rate.**

***Index Terms*—Renewable Energy Sources, Floating Solar, Wind Turbine, Grey Wolf Optimization, Economic Feasibility.**

I. Introduction

Solar and wind energy are two of the most promising renewable energy sources, as they are widely available and have a low environmental impact. In recent years, hybrid systems combining solar and wind energy have gained increasing attention due to their potential to improve energy efficiency and reliability. Bangladesh, a country located in South Asia, is facing significant energy challenges, including a lack of access to electricity and an over-reliance on fossil fuels. According to the World Bank, around 40% of the country's population does not have access to electricity, and the majority of electricity generation comes from fossil fuels [1], [2]. The use of renewable energy sources, such as solar and wind, can help to address these challenges and promote sustainable economic growth [3]. One potential area for the development of renewable energy in Bangladesh is the KEPZ and the development of a floating solar PV [4] and WT hybrid system at KEPZ can help to reduce the dependence on conventional power sources and lower greenhouse gas emissions. However, the optimal design and operation of such a hybrid system require consideration of various factors, such as weather conditions, energy demand, and economic viability [5]. However, the optimal placement of these technologies can be a complex problem, requiring consideration of factors such as resource availability, cost, and environmental impact. One approach to optimizing the placement of renewable energy technologies is through the use of optimization algorithms.

One such algorithm is GWO, which is inspired by the hunting behavior of grey wolves and has been used in various applications such as engineering design and image processing. One study by Hammed et al. (2020) investigated the optimal design of a hybrid wind-solar energy system using GWO. The results showed that the system could achieve a high level of energy efficiency and economic feasibility [6]. For example, [7] used GWO to optimize the placement of solar panels in a micro-grid system, while [8] used GWO to optimize the placement of WT in a wind farm. In the context of floating solar PV and WT, there has been relatively little research on the use of GWO. However, one recent study by ref [9] used GWO to optimize the placement of floating solar PV and WT in a hybrid renewable energy system. In the specific context of KEPZ in Bangladesh, there have been several studies on the potential for renewable energy development in the region. However, more research is needed to understand the specific challenges and opportunities for renewable energy development in KEPZ and to evaluate the potential benefits of using GWO in this context. The GWO algorithm is known for its simplicity, fast convergence, and ability to find optimal solutions efficiently. Compared to other meta-heuristic algorithms, such as Particle Swarm Optimization (PSO) [10] and Genetic Algorithm (GA) [11], Social Spider Optimization (SSO) [12], GWO requires fewer parameters to be tuned and has a lower computational cost. Therefore, it is an attractive option for optimizing large-scale and complex systems [13].

In this paper, GWO is chosen for its suitability for minimizing the operation cost of hybrid Solar and wind systems.

The main objectives are as follows —

- Design a grid-integrated floating PV, and WT system to evaluate the technical practicality based on hourly generation from given resource data.
- Estimates the upfront cost of the system considering equipment lifespan, installation capital cost, and maintenance cost to evaluate the economical feasibility.
- Optimize the annual cost by sizing the minimum equipment needed for the proposed model and do the price comparison with and without renewable resources.

II. Renewable Generation Potential in KEPZ, Chattogram, Bangladesh

Renewable energy generation has been gaining momentum in Bangladesh due to the country's abundant natural resources and growing demand for electricity. As of 2021, a total capacity of approximately 1,172 MW for renewable energy sources, which includes solar, wind, hydropower, and biomass energy are installed [14]. Solar energy is one of the most promising sources of renewable energy, with a current installed capacity of 746 MW nonetheless, wind energy has a potential capacity of 3,000 MW, although only a small fraction of this capacity has been utilized so far [14]. Meanwhile, biomass energy, such as biogas and biomass-fired power plants, has a potential capacity of up to 4,000 MW [14].

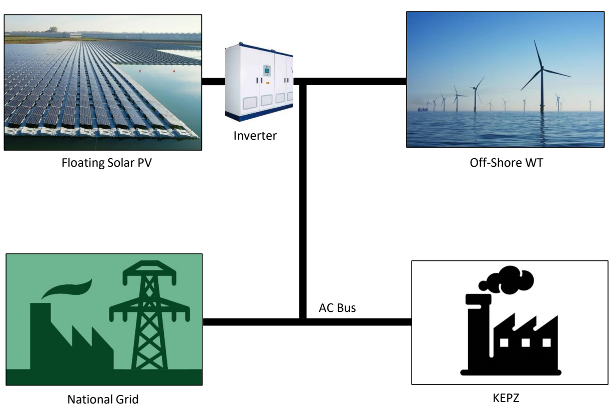

Fig. 1: Proposed Model

III. Model Formulation

The proposed model consisting of floating PV and WT integrated with the grid for the KEPZ model is shown in Fig. 1. Mathematical analogous equations are used for both technical and economical models of the component in order to estimate the annual hourly renewable generation and load consumption along with the investment cost and maintenance cost of the entire system.

A. Floating PV model

The energy generation from the floating PV is estimated using the mathematics model shown in EQ. (1). In order to simulate the floating solar considering the temperature effect on floating solar, The reference temperature is assumed 5% less as shown in [15].

$$E_{pv}(t) = PV_r \frac{G_h(t)}{G_S}\Big[1 + k_t\Big(T_{amb}(t) + 0.0256G_h(t) - T_S\Big)\Big] \quad (1)$$

Here, Photo-current (G_h), and the hourly radiation, G_S is radiation at STC, T_{amb} is the ambient temperature, and T_s is the hourly temperature.

The economic model of floating solar is used to determine the solar installation costs, maintenance, and operating costs over the project lifetime minus the salvage value remaining in a component at the end of the project lifetime [16]. The net present value of the solar panels is shown in EQ. (2).

$$TNPC_{pv} = I_{pv} + I_{pontoon} + OM_{pv} - S_{pv} \quad (2)$$

PV Investment Cost: Investment cost of solar photovoltaic panel is calculated using EQ. (3). The number of PV panels installed multiplied by their per unit cost would be the investment cost of solar panels. Per unit solar panel price was given on Table II.

$$I_{pv} = N_{pc} \times Per\ unit\ price_{pv} \quad (3)$$

PV Operation & Maintenance Cost: Solar plants operation and maintenance cost was calculated using the EQ. (4). All the O&M cost-related parameter is given in Table II.

$$OM_{pv} = \phi_{pv}.A_{pv} \sum_{k=1}^{N} \Big(\frac{1+\alpha_{pv}}{1+i}\Big)^k \quad (4)$$

PV Salvage Value Cost: Solar plant's salvage value remaining at the end of the project lifetime is calculated using the EQ. (5). All the salvage value-related parameter is given in Table II.

$$S_{pv} = \delta_{pv}.A_{pv}.\Big(\frac{1+\lambda}{1+i}\Big)^N \quad (5)$$

Floating Pontoon Investment Cost: A pontoon is a floating object constructed of polymer that has sufficient buoyancy to float on water while bearing a large weight. The unit price of the floating pontoon is given in Table II. The total investment cost regarding the Floating Pontoon is estimated using the EQ. (6).

$$I_{pontoon} = Total\ Area \times A_{pontoon} \quad (6)$$

Here, Per unit price $(A_{pontoon})$ is given on Table II. $Total\ Area$ of floating pontoon is estimated the $Number\ of\ PV\ Panel$ used times $(A_{pontoon})$.

B. WT model

The energy generation from the WT is estimated using the cubic model of wind function shown in EQ. (7) [19].

$$E_{wt}(t) = \begin{cases} 0 & V(t) \leqslant V_{cin} \text{ or } V(t) \geqslant V_{cout} \\ P_r^w & V_{rat} \leqslant V(t) \leqslant V_{cout} \\ P_r^w\Big(\frac{V(t)-V_{cin}}{V_{rat}-V_{cin}}\Big) & V_{cin} \leqslant V(t) \leqslant V_{rat} \end{cases} \quad (7)$$

TABLE I: Technical Parameter [11], [17], [18]

Equipment	Name	Symbol	Value
PV Panel	Power-Rating	PV_r	$435W$
	Radiation (STC)	G_s	$1000w/m^2$
	Reference Temperature	$Temp_{amb}$	$25°C$
Wind Turbine	Power-Rating	WT_r	$1000kW$
	Rated speed	V_{rate}	$12\ m/s$
	Cut-in speed	V_{in}	$3\ m/s$
	Cut-off speed	V_{out}	$23\ m/s$

Here, the Wind turbine model Vestas V90 (1000W) is selected and Pr_{wt} is the power generation capacity rating of each unit, V_{rate}, V_{in} and V_{out} are the rated, cut-in and cut-off wind speed (m/s) of each unit, respectively and these data are given on Table I. The turbine hub height and the measured reference wind speed can be correlated using the EQ. (8).

$$V(t) = V_r(t) \times \left(\frac{Hub_{WT}}{Height_{ref}}\right)^{\gamma} \tag{8}$$

Here, $\gamma = 1/7$ is assumed for the site to be well exposed to wind flow [11], $Height_{ref} = 10m$ is the height from where the meteorological data is measured and $Hub_{WT} = 20m$ is the height of the WT.

The economic model of the wind turbine is used to determine the installation costs, solar maintenance, and operating expenses during the project lifespan, less the salvage value still in a segment at the end of the project lifecycle. Wind Turbine's net present cost is estimated using EQ. (9).

$$TNPC_{wt} = I_{wt} + OM_{wt} - S_{wt} \tag{9}$$

WT Investment Cost: Investment cost of WT is calculated using EQ. (10). The number of WT installed multiplied by their per unit cost of equipment would be the investment cost. Per unit, WT price is given in Table II.

$$I_{wt} = N_{wt} \times Per\ unit\ price_{wt} \tag{10}$$

WT Operation & Maintenance Cost: Maintaining any system is expected some cost which is calculated using the EQ. (11). All the O&M cost-related parameter is given in Table II.

$$OM_{wt} = \phi_{wt}.A_{wt} \sum_{k=1}^{N} \Big(\frac{1+\alpha_{wt}}{1+i}\Big)^k \tag{11}$$

WT Salvage Value Cost: Salvage value of the WT is the remaining at the end of the project lifetime and is calculated using the EQ. (12). All the salvage value-related parameter is given in Table II.

$$S_{wt} = \delta_{wt}.A_{wt}.\Big(\frac{1+\lambda}{1+i}\Big)^N \tag{12}$$

TABLE II: Economic Parameters [17], [18], [20]

Components	Model	Parameters	Values
Solar PV	Solar Floating Pontoon	$A_{pontoon}$ ($\$/m^2$)	8
	SunPower E20/435W	A_{pv} ($\$/m^2$)	236.63
		α_{pv}	0.9
		δ_{pv} ($\$/m$)	$0.2A_{pv}$
		ϕ_{pv} ($\$/m^2/year$)	$0.011A_{pv}$
		lifespan (N_{pv})	25 Year
Wind Turbine	Vestas V90 2MW	A_{wt} ($\$/m^2$)	480
		α_{wt}	0.09
		δ_{wt} ($\$/m^2$)	$0.011A_{wt}$
		ϕ_{wt} ($\$/m^2/year$)	$0.0109A_{wt}$
		lifespan (N_{wt})	25 Year
Inverter	Sol-Ark 15KW	A_{inv} ($\$/kW$)	550
		α_{inv}	0.08
		δ_{inv} ($\$/kW$)	$0.001A_{inv}$
		ϕ_{inv}($\$/kW$)	$0.009A_{inv}$
		lifespan (N_{inv})	10 Year
Other Cost Paramter		interest rate (i)	0.1%
		lifespan (N)	25 Year
		inflation rate (γ)	0.0805

C. Inverter Model

DC to AC inverters models are designed to estimate the efficiency of changing DC energy generated by PV panels to the AC bus/load [19]. The ratio of the input and output power to the inverters is described as inverter efficiency (η_{inv}).

$$P_{AC,out} = P_{DC,in} \times \eta_{inv} \tag{13}$$

Here, inverter efficiency $(\eta_{inv} = 90\%)$ is assumed to estimate the total energy generated from the floating PV. The total net present cost, installation costs, inverter maintenance, and operating expenses during the project lifespan are estimated using the economic model of the inverter as shown below.

$$\begin{aligned} TNPC_{wt} &= I_{wt} + OM_{wt} - S_{wt} \\ I_{wt} &= N_{wt} \times \alpha_{wt} \\ OM_{wt} &= \phi_{wt}.A_{wt} \sum_{k=1}^{N} \Big(\frac{1+\alpha_{wt}}{1+i}\Big)^k \end{aligned}$$

IV. Economic Model

An economic model is developed using mathematical interpretation to estimate the annual cost for the proposed system to test the economic feasibility. The levelized cost of energy (LCOE) is the average revenue per unit of electricity produced that would be necessary to recoup the costs of constructing and operating an energy facility over its expected lifetime. LCOE is an important parameter to determine the economic feasibility of the system. LCOE for the grid-connected distribute generation model is estimated using the EQ. (14) [16].

$$LCoE = \frac{\sum(TNPC_{pv,inv,wt}).CRF + EG_{Buy}^{Net} - EG_{Sell}^{Net}}{\sum_{t=1}^{t_{max}=8760} Load(t)} \tag{14}$$

$$\begin{aligned} EG_{Sell}^{Net} &= \sum_{t=1}^{t=8760} (ESGH \times PUSgrid) \\ EG_{Buy}^{Net} &= \sum_{t=1}^{t=8760} (EBGH \times PUB_{grid}) \end{aligned} \tag{15}$$

Here, $ESGH$ is the energy sold to the grid per hour, and $EBGH$ is the energy bought from the grid per hour. Per kilowatt electricity retail price from Shikalbaha 150 MW Power station is $PUB_{grid} = 0.077\$sKwh$ [21] and the selling rate (PUS_{grid}) 70% off to retail price. $TNPC_{pv,wt,inv}$ is the total net present cost of the equipment used in the proposed model considering the interest rate, inflation rate, maintenance, and replacement required in the projected lifetime.

Capital Recovery Factor (CRF) is estimated using the EQ. (16) [22].

$$CRF = \frac{IR(1+IR)^T}{(1+IR)^T - 1} \tag{16}$$

Here, $IR = 8$ is the interest rate, and $T = 25$ is the projected lifetime for the proposed model.

A. Grey Wolf Optimization

The main purpose of using GWO is to optimally reduce the number of floating PV and the WT needed for the system to run economically feasible considering the installation cost and servicing cost over the equipment's lifespan. The algorithmic flow chart of the GWO operation is shown in Fig. 2.

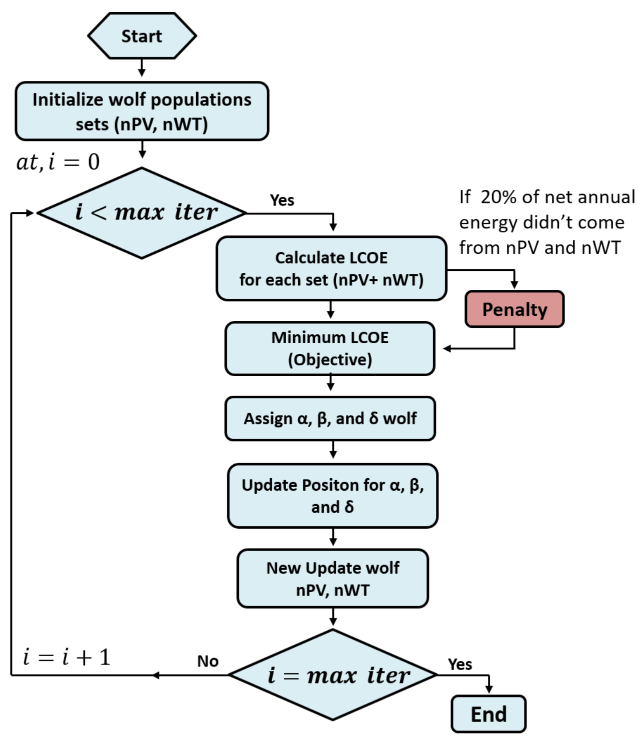

Fig. 2: GWO algorithm flowchart

The main decision variable of the optimization is the number of components that are required for the system to run economically feasible. The main boundary constraints are the maximum and the minimum limit of the amount of equipment tested against the location-specific data to test which configuration is more suitable. The limit constraints are $0 \leq NoC \leq 10000$, which means, the minimum renewable equipment could be zero and the maximum could be ten thousand. GWO will try to match 20% of renewable generation from the proposed system. If any configuration that consists of $0 \leq NoC \leq 10000$ of the renewable component cannot reach the threshold of 20% annual energy demand, that solution will automatically be penalized by the GWO, and will not considered as an optimal solution. Only those solutions that can achieve the annual defined load demand will be used as candidates for cost minimization.

V. Analysis Condition

The mathematically developed model responds to the given input data such as hourly solar resource and wind velocity data collected using HOMER NREL Tool [23]. The location-specific solar and wind resource data is shown in Fig. 3. The daily average DNI is noticed around 2.3 (kW/m^2), which is very potential for solar generation, and the average hourly wind speed is perceived around 4.26 (m/s).

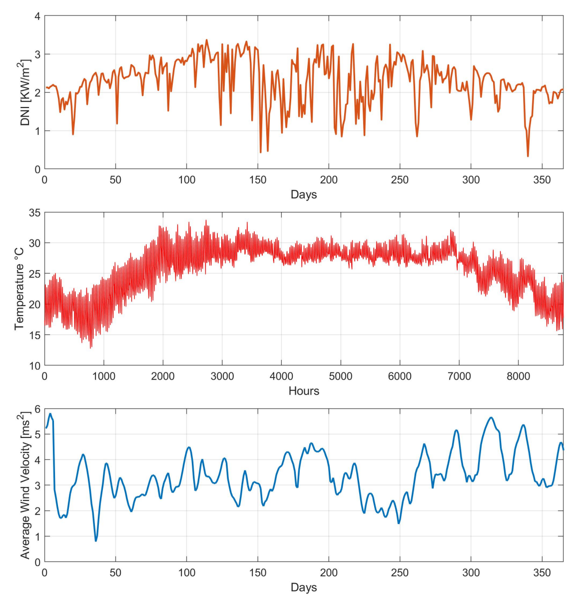

Fig. 3: Renewable Resource Data

The hourly energy consumption is collected from KEPZ. The hourly average load consumption data of each month is shown in Fig. 4. Maximum energy consumption is observed at $9.7MWh$ and the minimum energy consumption is $3.1MWh$. The average load consumption is around $4.84MWh$.

VI. Results & Discussions

This section addresses the economic feasibility of the proposed model, focusing on optimization results. The convergence curve shows the objective function's value plotted against computation time for minimization, achieved using optimization over 1000 iterations to determine the optimal size for the distributed renewable generator to run economically

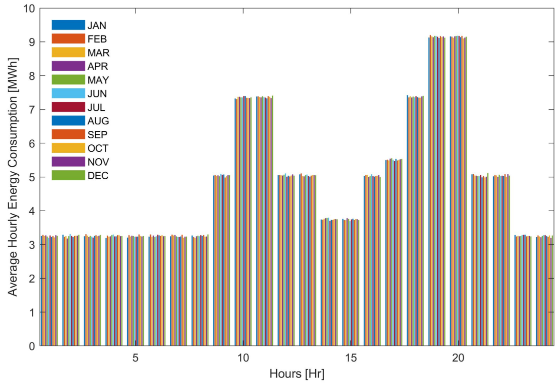

Fig. 4: KEPZ's hourly load demand

feasible. Then the annual hourly generation is estimated using that optimal-sized renewable generator.

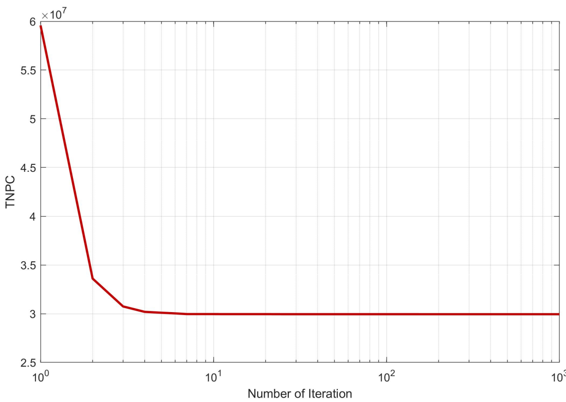

Fig. 5: Convergence Curve

The average hourly generation is found $942.22MWh$ for floating PV and $26.029MWh$ for WT. Peak renewable generation of the following system is found at $4757.5MWh$ and $368MWh$, respectively.

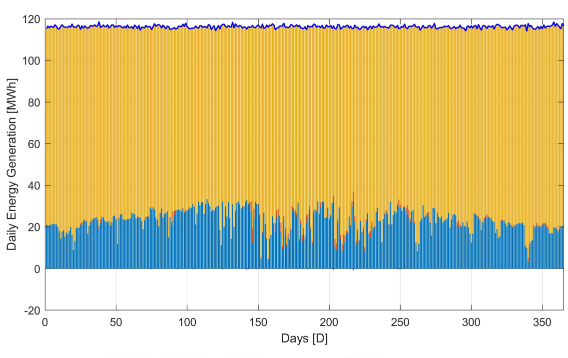

Fig. 6: Energy Provided by Renewable and Power Grid

The average daily generation from floating PV is found around $22613MWh$, and WT is found $624.69MWh$. where the rest of the energy is purchased from the Power grid. About 19% can be provided using a floating PV system, 1% can be provided using a wind turbine, and the rest of the 80% of the annual total energy demand of KEPZ needs to be bought from the grid. LCoE among existing grid, GWO-optimized hybrid renewable model, and non-optimized is shown in Fig. 8.

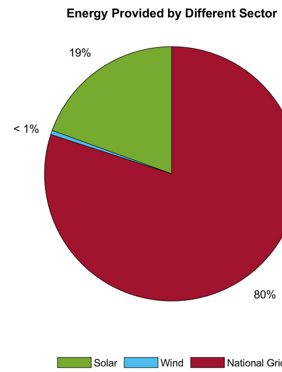

Fig. 7: Annual Energy Provided by Different Sectors

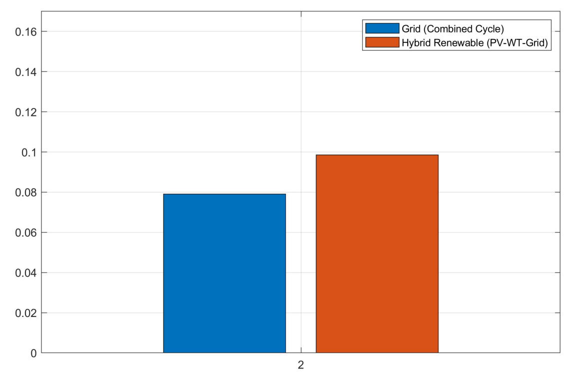

Fig. 8: Energy Provided by Renewable and Power Grid

GWO algorithm optimized the size of the renewable system based on the renewable resources' potentiality. For non-optimized LCoE, 1/5 of the load demand from renewable is taken, but the PV and WT capacity are assumed to be equal. Higher renewable LCoE of 0.16017 $(\$/kWh)$ is found compared non optimized renewable LCoE of $0.16017(\$/kWh)$ and Grid CoE is 0.079 $(\$/kWh)$.

A. Data Table

The optimal size of renewable capacity is determined by the GWO algorithm, which is shown in Table III.

The overall economic profile is shown in Table IV. $4,582,809 needed to be invested as capital cost. $25,318,453 of operation and maintenance costs will be spent over a project lifetime of 25 years. TNPC of the system is found

TABLE III: Annual generation of optimally sized System

DGs			Grid	
Name	Required Capacity (KW)	Annual Generation (MWh)	Energy Status (MWh)	
PV	886.53	8410.67	Sold	10.07
WT	80	78.25	Bought	33927.786
INV	4.85	0		

at $29,960,808. The LCoE is found 0.099 ($/KWh) for the proposed system. While considering energy purchase, 0.079 ($/KWh) is taken as the retail price and the selling cost is deemed to be 50% of the retail price.

TABLE IV: DG's Overall Cost

Floating PV and WT					Grid	
Name	Capital Cost ($)	O&M Cost ($)	NP Cost($)	LCoE ($/kWh)	Tariff Rate CoE ($/kWh)	
PV	7,13,300	16,407,726	17,171,976		Retail	0.079
Pontoon	50,000	0	0		Sell	50% of retail price
WT	88,000	33,73,709	3,461,709	0.106		
INV	78,898.96	96,960	1,94,772			
Total	9,31,149	19,878,395	20,828,456			

A total capacity of 8700kW of PV and 368kW of WT needs to be installed in the system to operate economically feasible to provide 20% of the total annual load demand at the KEPZ industrial zone. The rest of the 80% of energy is provided by Grid as shown in Fig. 7. From the floating PV system annual total of 8253.84 MWh and from the WT system 228.01MWh of renewable energy can be produced. A very negligible amount of wind energy is produced as it is tested with a low wind potential site.

VII. Conclusions

In this study, the economic and technical feasibility of distribute-generator such as floating solar PV panels, and off-shore WT for the KEPZ is tested for reliability of sustainable energy and also evaluated with TNPC and LCOE in terms of economic feasibility for the proposed model. With the novel and reliable Grey Wolf Optimizer, the optimal LCoE is found lowest as $0.099\$/kWh$ after 5 repeated runs. This cost of energy is quite high compared to the Power grid which is run by coal or gas.

However, the recent energy crisis event taught us to be less dependent on conventional methods. By using floating PV and WT 20% of the total annual energy demand of KEPZ can be fulfilled. As renewable technology is advancing further, fully green energy can be achieved within a couple of years. The approach also led to a substantial reduction in detrimental CO_2 emissions. Our objective is to conduct a comprehensive performance comparison of these algorithms against the optimized results we have achieved using the GWO approach.

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