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RESEARCH ARTICLE

Techno-Economic and Sensitivity Investigation of a Novel Perovskite Solar Cells Based High Efficient Hybrid Electric Sources for Off-Shore Oil Ships

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ABSTRACT Herein, this study presents for the first time third generation perovskite solar cells (PSCs) for enhancing the performance of off-shore oil ships. The off-shore oil ships need a high efficient hybrid solar energy- batteries system for enhancing the ships efficiency and reduce the pollutants resulting from these ships. In this study, an efficient model that consists of hybrid renewable energy system (HRES) suitable for the off-shore oil ships is presented and discussed. The model uses the PSCs as a solar energy source thanks to their high efficiency reaching now almost 26% based on nanotechnology in fabrication process. For determining the optimum quantities of the HRES model the HOMER software was used. The model succeeded in reducing the pollutants and the greenhouse gases (GHGs). The direction of the ship under study is from Dalian in China to Hurghada in Egypt where the data of electric load was chosen based on this journey which is real data. The full components of the model used are PSCs, Batteries and Diesel engine. Two PSCs arrays with 600 kW and 900 kW were used in the study beside 600 kW silicon based solar cells array for comparison between technologies of solar cells. The PSCs array were formed based on a laboratory fabricated PSCs that have 23.5 mA. Cm^{-2} as a short circuit current density, 1.085 V as open circuit voltage, 0.79 as a fill factor and 20.05% as a power conversion efficiency. The results revealed that the suggested model can help in reducing the total fuel consumption and the GHGs by 5,765,575 L and 15,592,017 kg for 600 kW silicon, 15,177,375 L and 15,662,875 kg for 600kW PSCs case, 17,634,350 L and 22,307,325 kg for 900kW PSCs case respectively related to using only diesel generator during the ship journey under the same conditions. Based on the obtained results, using the solar cells especially the recent technology base ones is attractive and highly recommended on the off-shore oil ships. This leading to both the fuel consumptions and cost reduction.

INDEX TERMS Perovskite solar cells, off-shore ships, batteries, diesel engine, techno-economic study.

I. INTRODUCTION

Third generation perovskite solar cells (PSCs) are high efficient solar cells fabricated based on nanotechnology with very low cost [1], [2], [3], [4], [5], [6], [7], [8]. The power conversion efficiency of PSCs reached almost 26% till now [9]. The PSCs thanks to their characteristics can help in efficient renewable energy based systems. The PSCs efficiency and stability can be enhanced and increased via surface passivation of electron transporting and perovskite layers [10],

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[11], [12], [13], [14], [15], also they can be improved via doping of both electron and hale transporting layers [10], [11], [12], [13]. New types of PSCs were fabricated and presented in literature where an improvement in the efficiency and stability was recorded [16]. The PSCs technology can be used to generate power from buildings windows based on the semi- transparent PSCs and the improvement in this area [17]. In the other hand the silicon based solar cells has also some enhancement for example diamond wire sawn (DWS) - processed multicrystalline silicon wafers which recently replaced the slurry wire sawn (SWS)- processed multicrystalline silicon wafers technique thanks to its merits, such as the low cost of the wafer and the increased yield productivity [18]. Multicrystalline silicon wafers use the DWS technology instead of SWS technology although it has a lack of compatible surface texturization process due to the high cost of the SWS technology [19]. Recently the hybrid silicon perovskite solar cells are under investigation.

The GHGs are produced in high amount beside other pollutants from the oil ships. This requires a solution for reducing these amounts. Recently, HRES are used in the ships instead of using only diesel engines for reducing pollutants and cost of fuel. Many studies had concluded that using storage batteries is high efficient method for reliability and quality of power systems and enabling big size distributed generation penetration on the electricity system [20], [21], [22].

A lot of studies in literature proved the efficiency of using hybrid solar energy, Diesel engine and batteries in supplying the loads efficiently in economic way and reducing the GHGs and pollutants at the same time. In [21] the authors have confirmed the optimal locations of distributed generations via optimization methodology in microgrid assuring maximum load ability. The hybrid renewable energy sources may be a mixed renewable energy systems or mixed renewable energy systems with conventional energy sources [1].

In [24] and [25] the authors presented and investigated a hybrid lithium-ion storage battery attached with diesel engine on ships and off-shore oil ships as a source of auxiliary power. For batteries life time increasing and fuel consumption decreasing some control approaches has been presented in previous studies [26], [27]. The authors in studies [28], [29], [30], [31] have used the hybrid model with and without batteries as storage devices where the proposed system successfully supplied the required load in an efficient way.

The hybrid photovoltaics/ Diesel engine/Batteries system to be used in off-shore oil ship is necessary to be investigated since it is very important topic. In literature there is a study that used Cold Ironing for ships GHGs reduction and making Taranto's ports environmental friendly [32]. In [33] the authors have examined the optimal sizing of a hybrid energy system consist of solar energy, batteries and diesel engine where they developed a methodology based on artificial intelligence for global tilted irradiance forecasting. In [34] the authors have proposed an efficient and optimal strategy of a hybrid solar and wind energy.

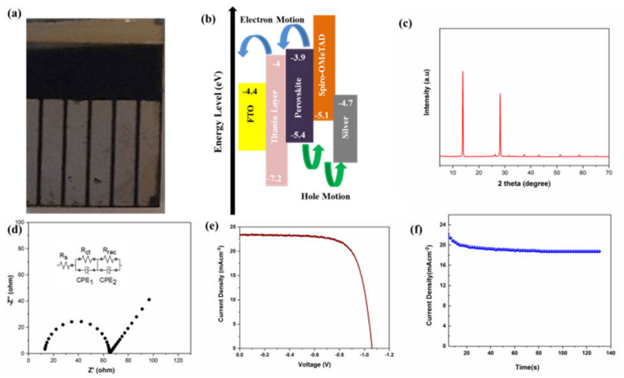

FIGURE 1. The PSCs full device (a), the PSCs device energy level diagram (b), the X-Ray of the perovskite absorber layer (c), the PSCs device impedance (d), the PSCs device current density- voltage relation (e), and the PSCs device maximum power point with time (f).

In this work, an optimal design of hybrid PSCs, Batteries, and diesel for off-shore oil ship is presented. The ship loads are actual loads of a ship travelling between China and Egypt. The study used HOMER software [35] for optimal designing of the system components where the PSCs are installed above the ship. The HOMER software contains a lot of arrangements of HRES. This software enabling optimizing and determining the different components sharing in the system. The proposed model results were compared with their analogy in using only diesel engine where the superiority and efficiency of the proposed model were clearly proved.

II. THE HYBRID PSCs/DIESEL ENGINE/BATTERIES MODEL FOR OFF-SHORE OIL SHIP

A. THE PSCs FABRICATION

The third generation perovskite solar cell used in this study is fabricated and characterized as follows; the Fluorine-doped tin oxide (FTO) conductive glass is cleaned by sonication in Hellmanex, 2-propanol, and acetone via 15 minutes sonication bath in each stage. After that the titania layer which is called electron transporting layer ETL is formed via spin coating deposition of titanium (IV) isopropoxide solution dissolved in ethanol and spin coated at 2000 rpm for 1 minute followed by heating at 500°C in oven for 45 minutes.

The main layer after the ETL is called the perovskite layer (absorber layer) is formed via spin coating of 40 wt % perovskite solutions formed from methyl ammonium iodide and lead acetate trihydrate in anhydrous DMF with a molar ratio of 3:1 and 10μl/ml a hypo phosphorous acid. The perovskite layer was deposited at 2000 rpm for 45 seconds then left to dry at room temperature for10 minutes and annealed for 5 minutes at 100 °C to form the perovskite layer. After the perovskite layer the hole transporting layer (HTL) is formed via deposition of a 70 mM Spiro-MeOTAD solution in chlorobenzene at 4000 rpm for 10 seconds. Lastly, a 100 nm silver electrodes were formed via thermal evaporation of silver wire under a 10^{-6} Torr vacuum at a 1 Å s−1. The fabricated PSCs device and its characteristics is shown in

TABLE 1. **The Solar cells modules characteristics.**

Solar cells system		
The technology	Silicon based solar cells	Perovskite solar cells
Power rate	600 kW	600 and 900 kW
Derating factors	85%	85%
The Capital costs	1,600$	200$
The replacement costs	1,400$	180$
Operating and maintaining cost	Zero	Zero
No. of years	25	25

Figure 1. The PSCs device parameters such as open circuit voltage, short circuit current external quantum efficiency (EQE) and internal quantum efficiency (IQE) were recorded via a solar simulator. The obtained PSCs parameters were 23.5 mA.Cm^{-2} as a short circuit current density, 1.085 V as open circuit voltage, 0.79 as a fill factor and 20.05% as a power conversion efficiency.

B. DISSIMILARITY BETWEEN HYBRID PSCs/ DIESEL ENGINE/BATTERIES SYSTEM ON OFF-SHORE OIL SHIP AND LANDS

Implementing and optimally design the hybrid solar energy (photovoltaics)/ Diesel engine/ Batteries system as a standalone system in off-shore oil ships is totally different from applying the same system in isolated models on a land. The difference comes from the following points, (1) The load nature where the load on the land is fixed while, the load on oil ship changes with the ship position (it is movable load) [36]. (2) The solar irradiation is almost constant on the land standalone system while it varies with ship position on its way due to the continuous changes in longitude and latitude and also the dates of the ship sailing [37]. (3) The nature of the working area, where in the sea and oceans there is waves crashing resulting in water on ship surface that affecting the operation of photovoltaics on ship surface while this case isn't applicable in the land system. (4) HRES on oil ship reliability should be 100% for safe sailing while the 100% reliability of the same system on land system is not required [38], [39]. (5) The incidence angle in the stand alone model on the land is constant at a moment while, it changes in ships case due to fluctuations of sailing ships.

C. THE OFF-SHORE OIL SHIP COMPONENTS EXPLANATION

In this work the sizing of optimal hybrid PSCs/Diesel/Batteries feeding the load on oil ships is investigated. The oil ship in this study has 330 m∗ 62 m as area, its height is 32 m and it weighs 100,000 tons. The sailing time for the ship is 25 days from the Dalian in China to the Hurghada in Egypt or the opposite. In this study it is supposed that the ship makes 6 trips in the year in different months. The outcomes from this study are the cost and emission analysis of the proposed hybrid PSCs/Diesel/ Batteries system for feeding the ship loads. HRES in oil ship is presented in Figure 2. The optimum

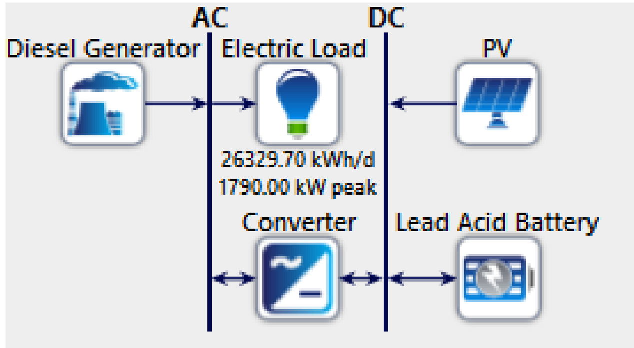

FIGURE 2. **The HRES components configuration.**

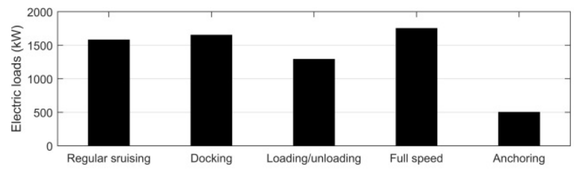

FIGURE 3. **The five loads of the off-shore oil ship.**

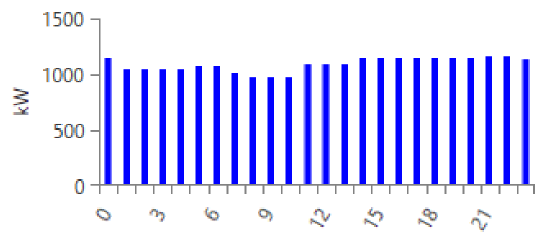

FIGURE 4. **The HRES load profile.**

system is the hybrid PSCs/Diesel/ Batteries where the PSCs and the diesel generator produce the necessary power for the load while the batteries are used for storing the spare energy and increase the reliability of the system. The components costs and description of HRES used in this study to run the HOMER software is obtained from [40] and [41] where, Table 1, gives the solar cells modules data. The converter power rate is1000 W, capital cost is 500$, replacement cost is 450$, Operating and maintaining cost is 5 $/yr, No. of yrs is 15 and efficiency is 90%. The 25 years is chosen as project life time at 8% interest rate in a year and a zero capacity shortage in this study.

The battery type is lead acid with 83.4Ah power rate, 50$ capital cost, 45$ replacement cost, 20 years and 80% efficiency. The diesel generator model is Genset (2MW) with power rate of 2MW, 25% least load ratio, 280,000 $ capital costs, 260,000 $ replacement costs, 0.25 $/hour operating and maintaining costs and 25,000 working hours.

D. THE ELECTRIC LOAD OF THE OFF-SHORE OIL SHIP UNDER INVESTIGATION

The study covers five actual types of loads. The load of the off-shore oil ship inequality per hour is reflected in different operational modes along the ship sailing route. The loads on this study are presented in Figure 3. The loads considered in this study are regular cruising (1,580 kW), Docking (1,650 kW), Loading –unloading (1,290 kW), Full speed (1,790 kW) and anchoring (500 kW). The peak load happens at full speed of the ship which is 1790 kW in this study while the least load is 500 kW at anchoring case. The proposed PSCs/ Diesel engine/ Batteries HRES is used for feeding the maximum load. The proposed system will feed the highest loads. The oil ship under investigation in this study make 7 stops during its journey for maintenance and exchanging. These 7 stops are Dalian then Shanghai followed by Hong Kong in China after that Singapore, Matara in Sri-Lanka, Aden port in Yemen and finally Hurghada in Egypt. The daily load profile of the HRES for the oil ship traveling from Dalian in China to Hurghada in Egypt is displayed in Figure 4.

E. THE SOLAR IRRADIATION PROFILE ON OIL SHIP ROUTE

The oil ship route is passing through seven stops and at each zone the climate is different. The irradiation along the sailing route changes due to longitude, latitude the date, the time zone, the day and the month. The co-ordinations and the yearly average solar irradiation at the seven stops cities on the route of oil ships under investigation for 22 yrs, period data till June 2005 were obtained from NASA database [42]. In this study the average annual irradiation of the seven stops cities in oil ship sailing route is one of the inputs of HOMER software.

III. RESULTS AND DISCUSSIONS

The software used in this study for optimizing the hybrid PSCs/ Diesel engine/ Batteries is HOMER software developed in United States national renewable energy lab for the purpose of renewable energy systems optimization. This software enables modeling, optimizing and sizing of renewable energy systems with conventional sources like diesel generators and determines the cost of each combination beside calculation of the energy flows from and to every component in the system. The HOMER software is accurate software since it runs for the thousands of simulations scenarios at each hour for obtaining the best matching between the load demand and the generation source. The HOMER software optimization results for off-shore oil ship are presented in Tables 2, 3 and Figures 5 to 7, for the three studied cases (600 KW Silicon based solar array, 600 kW and 900 kW PSCs based array). From Table 2 and Figure 5, it is obvious that the optimum system has the least amounts for the fuel consumptions (2,274,532 L/yr) for the proposed PSCs (600 kW)/ Diesel/ Batteries system. The results revealed that the fuel consumption at hybrid PSCs/ Diesel is 2,335,783 L/yr while it is raised to 2,506,086 L/yr for a Diesel/Batteries combination followed by a 2,506,204 L/yr for Diesel only. The proposed system has been compared with the first generation silicon solar cells (600 KW) instead of third generation PSCs based system under the same conditions to show the effect of using the recent PSCs and the HOMER software optimization results for off-shore oil ship as shown in Figure 6. From Table 3 and Figure 6, the least amount of fuel consumption is at hybrid Silicon solar cells (600 kW)/ Diesel/ Batteries with 2,561,004 L/yr while it is 2,673,156 L/yr at hybrid silicon solar cells (600 kW)/ Diesel raised to 2,881,509 L/yr for a Diesel/Batteries combination followed by a 2,881,627 L/yr for Diesel only. The PSCs penetration amount in the proposed model is also increased to 900 KW and the calculations has been repeated as displayed in Figure 7. From Figure 7, again a hybrid proposed model has the lowest consumption fuel at 2,196,253 L/yr. For all cases the diesel is a main source of electricity feeding the load thus the diesel operating hours is constant in all configurations and it is 7200 hours that represents 12 trips in 25 days (12∗25∗24) in a yr. The proposed hybrid PSCs/Diesel/Batteries system reduces the fuel consumptions by 15,177,375 L for 600 kW PSCs case, 5,765,575 L for 600 kW silicon solar cells and 17,634,350 L for 900 kW PSCs case.

Through project period at using only Diesel engine in the off-shore oil ship under the same conditions. As a result, high penetration of PSCs as a source of electricity on oil ships is highly recommended and will decrease both the fuel consumptions and cost. The average monthly production of electricity for the different combination of the HRES is presented in Figures 5 to 7. Based on these results, the diesel feeding the load with 88.2% and the PSCs with 11.8%. For the silicon solar cells case it shows that the optimum system requires (89.25% from diesel and 10.75% from the silicon solar cells to feed the load as displayed in Figure 6. While, it requires 17.4% from PSCs at rating of 900 KW and 82.6% from diesel engine as indicated in Figure 7. This is due to both the rating and the cost difference where the cost of the perovskite solar cells based array is lower than the cost of the silicon based array due to the merits of the third generation perovskite solar cells especially the low fabrication cost.

Based on the above results the proposed system with PSCs is the best solution as a HRES for feeding the load of off-shore oil ship.

A. ECONOMIC ASSESSMENTS

Firstly, some economic analysis factors and method is presented as follows [43].

- ✓ The capital cost: is the cost of the establishing instruments of the project.
- ✓ Operation and maintenance cost (OM): is the cost of maintenance throughout a life time for the project.
- ✓ Replacement cost (C_{rp}): is the changing cost of any element.
- ✓ Salvage value: the component value when the project time runout. The equation used to assess a salvage value is as follows:

$$Sc = \frac{C_{rp}R_{rm}}{R_{cm}} \tag{1}$$

where Sc indicates the salvage costs, C_{rp} symbolizes component replacement costs, R_{rm} denotes the element residual life, and R_{cm} presents the element lifetime.

TABLE 2. The optimization results of HRES system components for 600 kW PSCs case.

	PV (kW)	Diesel gen. (kW)	Battery(MWh)	Converters(kW)	LCOEs ($/kWh)	NPCs (M$)	RFs (%)	Total Fuel (L/Y)
PSCs/ diesel/ battery/converter	600	2000	50	300	0.251	31.2	9.88	2274532
PSCs /diesel /converter	600	2000	-	600	0.255	31.6	7.27	2335783
diesel	-	2000	-	-	0.27	38.4	0	2881627
diesel/ battery/converter	-	2000	1	50	0.271	38.4	0.0044	2881509

✓ The life cost cycle (LCCs): is the sum of all costs in the project and it is assessed as follows:

$$LCCs = Intial \text{ cost} + OM + Fc + \text{Crp} + Sc \tag{2}$$

where Fc is the fuel cost, The HOMER software uses all above costs beside fuel cost to calculate the annualized cost. The economic feasibility for a system is evaluated based on LCCs as a result the system with lower LCCs is the best.

✓ The cost of operation: represents the annual assessment of the total costs, revenues and the capital cost as shown in a following equation.

$$C_{op} = C_{ot} - C_{acp} \tag{3}$$

where, C_{op} is the operational costs, C_{ot} is the total annualized costs and C_{acp} is the total annualized principal costs.

✓ Fuel cost which is the cost resulted from multipling the fuel consumptions for the diesel engine by the fuel price.

1) ENERGY COST

Cost of energy (COEs) is the average cost/ kW produced and it calculated by dividing the total annual cost for electricity generation by the total useful generated power as equation (4):

$$COEs = \frac{C_{att}}{E_{cc}} \tag{4}$$

where C_{att} is the total cost in the yr in \$. E_{cc} is the overall electricity consumption in kWh/yr. From Figure 5, the COEs of the proposed hybrid PSCs (600 kW)/ Diesel/ Batteries is the lowest in all combinations at 0.251 \$/kWh. The COEs of other system arrangements (PSCs/ Diesel engine), (Diesel engine) and (Diesel engine /Batteries) are 0.255 \$/kWh, 0.268 \$/kWh and 0.269 \$/kWh respectively. While at using silicon solar cells 600kW the lowest COEs value is 0.259 \$/kWh and is 0.243 \$/kWh at using 900 kW PSCs all the lowest values are at the combination of hybrid solar energy/Diesel/ Batteries.

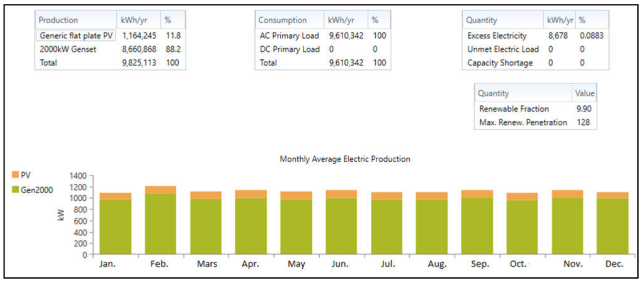

FIGURE 5. The monthly average production for 600kW PSCs case.

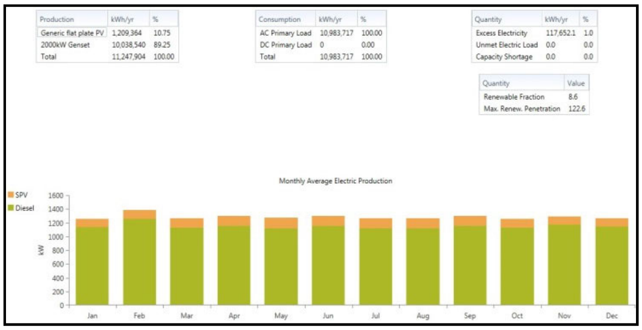

FIGURE 6. The monthly average production for 600KW silicon solar cells case.

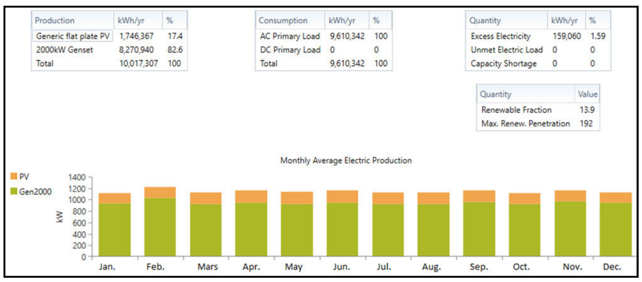

FIGURE 7. The monthly average production for 900 KW PSCs case.

The optimal system encloses 600kW of PSCs system, 2 MW diesel generator, 50,000 storage batteries, and 300kW of power converters at 600 kW PSCs case. The optimum system at using 600kW silicon solar cells has 600 kW of silicon solar cells, 2 MW diesel generator, 10,000 storage lead acid batteries, and 400kW of converters and it has 900 kW of silicon solar cells, 2 MW of a diesel, 50,000 storage lead acid batteries, and 600 kW of power converters at the case of using 900 kW PSCs.

2) THE NET PRESENT COST

The net present cost (NPCs) contains all revenues and prices which appear in the life time for a project. HOMER software calculates the NPCs based on a following equation:

$$NPCs = C_{att}/CRFs_{(jk)} \tag{5}$$

where C_{att} symbolizes the total annualized cost, j denotes the annual real interest rate, k represents the project duration, and capital recovery factors (CRFs) is given by:

$$CRFs = jj(1+jj)^{nm}/[jj(1+jj) - 1] \tag{6}$$

TABLE 3. The optimization results of the HRES system components for 600 kW silicon solar cells case.

	PV (MW)	Diesel generator(MW)	Battery (MWh)	Converters(kW)	LCOEs ($/kWh)	NPCs (M$)	RFs (%)	Total Fuel (L/Y)
PV/diesel/battery/converter	0.6	2	10	400	0.259	32	8.6	2651004
PV/diesel/converter	0.6	2	-	600	0.261	32.5	7.8	2673156
diesel	-	2	-	-	0.27	38.4	0	2881627
diesel/battery/converter	-	2	1	50	0.271	38.4	0.004	2881509

TABLE 4. The greenhouse gases amount at different HRES arrangements.

	Silicon solar cells/Diesel/Battery (Kg/yr)	Silicon solar cells/Diesel (Kg/yr)	Diesel/ Battery (Kg/yr)	Diesel (Kg/yr)
Carbon Dioxide	6,980,965.5	7,039,300.3 3	7,587,961. 4	7,588,272. 5
Carbon Monoxide	17,231.52.5	17,375.522	18,729.81 2	18,730.58 1
Unburned hydrocarbons	1,908.725	1,924.671	2,074.691	2,074.771
Particulate Matter	1,298.995	1,309.851	1,411.943	1,412.3
Sulfur Dioxide	14,019.4	14,136.142	15,237.95 2	15,238.57. 2
Nitrogen Oxides	153,758.5	155,043.4	167,127.3	167,134.2

	PSCs/Diesel/Battery (Kg/yr)	PSCs / Diesel (Kg/yr)	Diesel/ Battery (Kg/yr)	Diesel (Kg/yr)
Carbon Dioxide	5,989,591	6,150,885	6,599,348	6,599,659
Carbon Monoxide	14,784	15,183	16,290	16,290
Unburned hydrocarbons	1,638	1,682	1,804	1,804
Particulate Matter	1,115	1,145	1,228	1,228
Sulfur Dioxide	12,028	12,352	13,253	13,253
Nitrogen Oxides	131,923	135,475	145,353	145,360

where, nm depicts the yrs number. From Figure 5 the NPCs for the combinations of the HRES can be obtained. Obviously, the optimal (PSCs/Diesel/Batteries) system have the minimum NPCs of 31.2 M$, then the (PSCs/Diesel) combination at NPC of 31.6 M$, NPCs for the third combination (Diesel generator) is 33.3 M$ and lastly (Diesel generator/ Batteries) combination at NPC of 33.4 M$ at 600 KW PSCs, and it is 36.7M$, 37M$, 38.4M$ and 38.4M$ respectively at using 600 kW silicon solar cells while, the NPCs at using 900 kW PSCs are 30.1 M$, 30.8 M$, 33.3 M$ and 33.4 M$

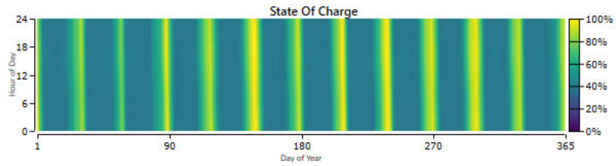

FIGURE 8. The batteries state of charge at 600 kW PSCs optimal arrangement.

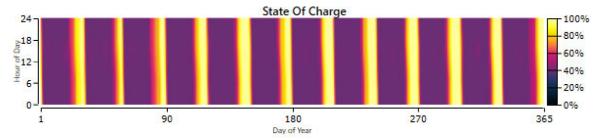

FIGURE 9. The batteries state of charge at 900 kW PSCs optimal arrangement.

respectively. The results revealed the superiority of the proposed system and the proposed PSCs.

B. THE EMISSIONS ANALYSIS

The results showed a reduction in the contaminants emission. The renewable fraction (RFs) in the hybrid solar energy /Diesel /Batteries is the sharing ration of different resources. The solar energy (photovoltaic) fraction is F_{PV}, and the fraction of Diesel engine is zero. F_{PV} is calculated via the following equation:

$$F_{PV} = \frac{E_{PV}}{E_{att}} \tag{7}$$

where, E_{att} is the total loads (kWh/yr), and E_{pv} denotes the generated energy from the solar energy (kWh/yr). Based on Figures 5 to 7, the optimal model has 0.089 RFs at using 600 kW PSCs, 0.086 RFs at using 600 kW silicon solar cells and 0.139 RFs at using 900 kW PSCs. Table 4 displays the GHGs amounts resulted from various hybrid sources configurations. Based on the data presented in Table 4 it is clear that the proposed PSCs/Diesel /Batteries system produce lower GHGs emission compared to other systems (PSCs/Diesel, Diesel/ Batteries, and Diesel). The solar energy is used on oil ship for reducing the GHGs because it is very harmful for human health and life.

C. THE HYBRID RENEWABLE ENERGY SYSTEM COMPONENT TECHNO-ECONOMIC INVESTIGATION

The irradiation falls on the solar array resulting in electric energy and generated energy is directly proportional to the incident irradiation. HOMER software designed the solar energy output as follows:

$$P_{PV} = F_{PV} C_{PV} (Gr/Kr) \tag{8}$$

where CPV is the assessed capability for the solar energy system (kW), Gr is the overall solar irradiation falls on a surface of solar energy system array (kWh/m^2), Kr is 1kW/m^2 and FPV is the solar energy system derating factor. An 80 % derating factor is used to consider the effect of temperature, shading, dust effect and aging. The average power for PSCs

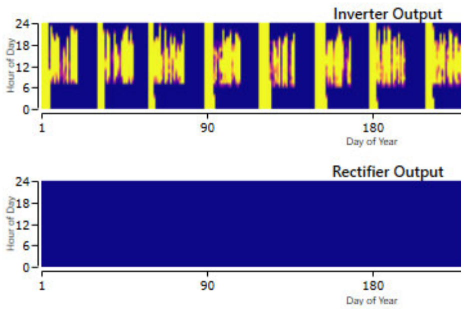

FIGURE 10. The converter output at 600 kW PSCs/Diesel engine/ Batteries system.

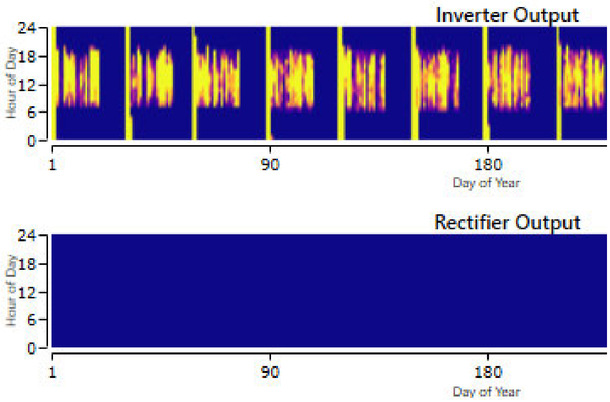

FIGURE 11. The converter output at 900 kW PSCs /Diesel engine/ Batteries system.

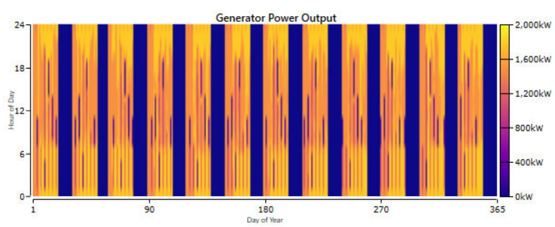

FIGURE 12. The diesel generator output at 600 kW PSCs.

FIGURE 13. The diesel generator output at 900 kW PSCs.

through the day is 3,313.334 kWh/d and the assessed capacity is 600kW and 900kW while the silicon solar cells rated capacity is 900kW, a capacity factor of 23.015%, and 4,439 working hours.

1) THE LEAD ACID BATTERIES

The solar energy system output depends on the incident irradiation and this irradiation is changing resulting in changing

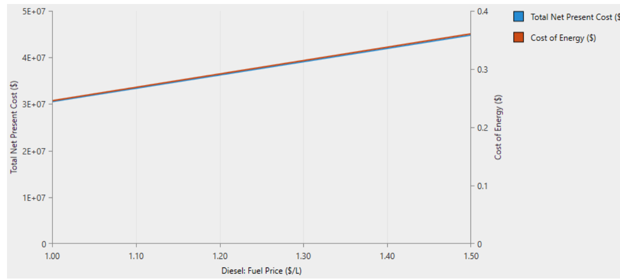

FIGURE 14. Optimal model for variant fuel price at fixed load and solar irradiation 6 kWh/m^2 per a day, case of 600 kW PSCs.

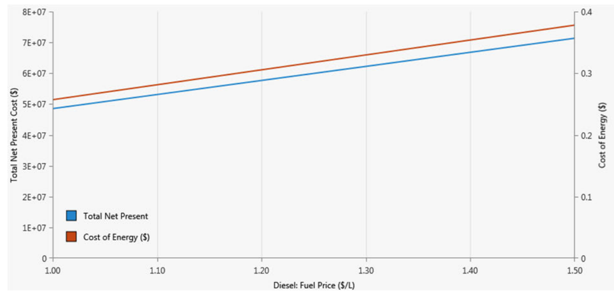

FIGURE 15. Optimal model for variant fuel price at fixed load and solar irradiation 6 kwh/m^2/day, case of 600 KW silicon solar cells.

TABLE 5. Renewable fraction based sensitivity analysis.

600 kW based Silicon solar cells						
RFs%	Engine kW (Diesel)	Batteries	Converters in kW	COES $/kWh	NPCs$	RFs%
0	2000	1000	400	0.259	2.65M	8.61
10	2000	1000000	400	0.321	2.51M	13.8
30	2000	3000000	400	0.45	2.27M	22.6
600 kW based perovskite solar cells						
RFs%	Engine kW (Diesel)	Batteries	Converters in kW	COES $/kWh	NPCs$	RFs%
0	2000	50000	300	0.251	31.2M	9.88
10	2000	50000	400	0.251	31.2M	10.1
30	2000	2000000	600	0.395	49.1M	20

the power from the solar energy system. A battery is necessary to store and smooth the system output it stores the energy when the generated energy is higher than the load and discharge when the generated power is lower than the load. Figure 8 and Figure 9 shows the batteries state of charge (SOC) at optimal arrangement (PSCs/Diesel/Batteries) at 600 kW and 900 kW case respectively.

2) THE POWER CONVERTERS

The power converter has two working case, the inverter case and rectifier case the operation cases for 600 kW PSCs case are shown in Figure 10 while the same cases for 600 kW silicon solar cells are presented in Figure 11.

3) THE DIESEL UNITS

The diesel generator is the base source since it used to feed electrical loads when the solar energy and the batteries are in sufficient. The used diesel generator in this study is 2 MW under 25% from the output as minimum operating ratio. The diesel engine life time depends on its working hours. The diesel generator life hours in HOMER software is determined by the following formula:

$$G_{Lly} = G_{Llh}/N_{hlg} \quad (9)$$

where, G_{ly} denotes the diesel engine yearly, G_{llh} symbolizes the diesel generators life in hours and N_{hlg} is number of working hours of diesel engines in a year (h/yr). Figure 12, presents the diesel generator output power at the case of hybrid PSCs/Diesel/ Bateries at 600 kW PSCs and Figure 13, presents the same case at using 900 kW PSCs.

D. THE SENSITIVITY ANALYSIS

In this study both the solar radiation and RF uncertainties are reflected in the HOMER software simulation for the proposed HRES combinations.

1) RELATION BETWEEN COST OF ENERGY AND DIESEL FUEL PRICE

The Cost of energy and NPC are directly proportional to the diesel engine fuel cost and this is obvious in Figures 14 to 15.

2) RENEWABLE FRACTION SENSITIVITY ANALYSIS

The sensitivity analysis of RFs is presented in Table 5 where the RFs is higher than 0%, 10% and 30%. The results showed that the smallest COES is at RFs equal to 8.61% and this COES is 0.259$/kWh at 600 kW silicon solar cells. While, the lowest COES at using 600 KW PSCs equal to 0.251$/kWh and it is at RFs equal to 0% to 10%.

IV. CONCLUSION

In this work, a high efficient proposed model consists of PSCS, Batteries and diesel engine was designed and investigated for application in off-shore oil ships. The results revealed the superiority and efficiency of the model. The optimum quantities of the energy produced from the model components were determined via HOMER software. The software also performs the economic and environmental impacts investigation. A different five actual load states were studied and taken from areal case of travelling ship from China (Dalian) to Egypt (Hurghada). The system reliability is 100% since the proposed model is designed via a common HOMER software that has a yearly 0% as a shortage capacity. The proposed model consists of 600, 200, 10000, and 400 kW for the PSCs, Diesel, Batteries and the power converters respectively as optimal quantities. The proposed combination is the best among all combinations since it has the following merits:

In the case of 600 kW PSCs the proposed combinations have the smallest NPCs and COES of 30.1M$ and 0.251 $/kWh correspondingly with the largest RFs of 10%, also it has the least values of NPCs and COES at the case of 600 kW silicon based which are 36.7 M$, 0.259 $/kWh correspondingly at RFs equal 8.6%.

The GHGs is reduced thanks to the proposed combination in comparison with using only diesel engine for feeding the load.

The proposed combinations save the fuel consumptions and decrease its cost.

As a result, the proposed model that based on PSCs proved its superiority and efficiency. The model is highly recommended to be used in off-shore oil ships to reduce the greenhouse gases, pollutants and fuel cost. More efficient and stable third generation solar cells based on nanotechnology in fabrication as a photovoltaic source for feeding electrical loads at low cost including oil ships is considered for future work.

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