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A Comprehensive Study on the Performance of Various Tracker Systems in Hybrid Renewable Energy Systems, Saudi Arabia

Mohana Alanazi [1,*], Hani Attar [2], Ayman Amer [2], Ayesha Amjad [3,4], Mahmoud Mohamed [5,*], Mohammed Sh. Majid [6], Khalid Yahya [7] and Mohamed Salem [8]

1 Department of Electrical Engineering, College of Engineering, Jouf University, Sakaka 72388, Saudi Arabia
2 Department of Engineering Energy, Zarqa University, Zarqa 13133, Jordan; hattar@zu.edu.jo (H.A.); aamer@zu.edu.jo (A.A.)
3 Faculty of Organization and Management, Silesian University of Technology, 44-100 Gliwice, Poland; ayesha.amjad@polsl.pl
4 Centre for Mechanical Engineering, Materials and Processes (CEMMPRE), University of Coimbra, Polo II, 3030-788 Coimbra, Portugal
5 School of Engineering, Cardiff University, Cardiff CF24 3AA, UK
6 Computer Techniques Engineering Department, Al-Mustaqbal University College, Babylon 51001, Iraq; mohammed.shawkat@uomus.edu.iq
7 Department of Electrical and Electronics Engineering, Nisantasi University, Istanbul 34467, Turkey; khalid.yahya@nisantasi.edu.tr
8 School of Electrical and Electronic Engineering, Universiti Sains Malaysia (USM), Nibong Tebal 14300, Penang, Malaysia; salemm@usm.my
* Correspondence: msanazi@ju.edu.sa (M.A.); mohamedmt@cardiff.ac.uk (M.M.)

Abstract: To compensate for the lack of fossil fuel-based energy production systems, hybrid renewable energy systems (HRES) would be a useful solution. Investigating different design conditions and components would help industry professionals, engineers, and policymakers in producing and designing optimal systems. In this article, different tracker systems, including vertical, horizontal, and two-axis trackers in an off-grid HRES that includes photovoltaic (PV), wind turbine (WT), diesel generator (Gen), and battery (Bat) are considered. The goal is to find the optimum (OP) combination of an HRES in seven locations (Loc) in Saudi Arabia. The proposed load demand is 988.97 kWh/day, and the peak load is 212.34 kW. The results of the cost of energies (COEs) range between 0.108 to 0.143 USD/kWh. Secondly, the optimum size of the PV panels with different trackers is calculated. The HRES uses 100 kW PV in combination with other components. Additionally, the size of the PVs where 100% PV panels are used to reach the load demand in the selected locations is found. Finally, two sensitivity analyses (Sens) on the proposed PV and tracker costs and solar GHIs are conducted. The main goal of the article is to find the most cost-effective tracker system under different conditions while considering environmental aspects such as the CO_2 social penalty. The results show an increase of 35% in power production from PV (compared to not using a tracker) when using a two-axis tracker system. However, it is not always cost-effective. The increase in power production when using vertical and horizontal trackers (HT) is also significant. The findings show that introducing a specific tracker for all locations depends on renewable resources such as wind speed and solar GHI, as well as economic inputs. Overall, for GHIs higher than 5.5 kWh/m^2/day, the vertical tracker (VT) is cost-effective.

Keywords: tracker; HRES; solar; wind; HOMER

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1. Introduction

Renewable energies are one of the best choices to supply load demand in both grid-connected and remote areas to reduce CO_2 emission [1]. Emission of greenhouse gases such as CO_2 is highly dependent on the energy systems of the countries [2], where the residential sector's share in emission is remarkable [3]. In Saudi Arabia, there are remote areas that can be supplied by stand-alone systems in addition to grid-connected ones [4]. The high potential of available wind and solar energies in the country [5] makes it a good option to investigate the feasibility of power generation in more than 40 remote areas [6]. These areas cannot be supplied by the national grid, and due to the fluctuations of the renewable resources over the year (yr), HRES such as PV, WT, Gen, and Bat would be an effective solution to avoid grid extensions [7–9]. The combination of PV, WT, Gen, and Bat would cause high reliability of electricity production where one of the resources is not sufficient [10]. Wind and solar energy vary over time due to changes in weather conditions, which can happen daily, weekly, or seasonally [11,12]. A recommended solution is to use a hybrid system that combines multiple energy sources to meet the electrical load while maintaining a suitable renewable fraction (RF), low LCOE, and minimal or zero GHG emissions [13,14]. Solar radiation in Saudi Arabia varies between 4 to 7.5 kWh/m^2/day and wind speed in some regions ranges between 4–8 m/s. This can fulfill electricity production from PV panels and wind turbines, respectively [15]. Due to a 7.5 to 10% annual increase in electricity consumption, the government has decided to develop renewable energies' share in the total power supply under a plan named Vision 2030 [16]. The government has imposed electricity tariffs and energy efficiency factors to encourage the production of low-pollution power at peak hours (h) when solar irradiance is high [17]. Since Saudi Arabia has the highest electricity production from non-clean energies such as fossil fuels, its CO_2 production plays a pivotal role among other countries [18]. To solve this problem, the government is encouraging the private sector to invest in clean energy production, resulting in an increase in related jobs [19]. In this respect, investigating different optimum hybrid renewable systems and finding the best configuration (Config) of each component would be rational work. In Table 1, the details of some of the previous studies on off-grid HRESs including PV/WT/Gen/Bat are presented. One issue regarding components that needs to be addressed is whether PV panels should include tracker systems or not. In the following, a brief review of tracker systems and some related studies conducted for Saudi Arabia are provided to clarify this matter.

The sun's position is determined by azimuth angle, altitude angle, and GPS coordinates. The latter is constant, while the former two vary due to the Earth's rotation and orbit. Researchers use tracking mechanisms to maximize sunlight harvesting [20]. A tracking system that keeps panels perpendicular to sunlight maximizes energy output. Solar tracking can boost energy production by 30–60% over fixed systems [21,22]. Tilted solar panels are used to convert solar energy into electricity. These systems can operate at a fixed-tilt angle, track the sun on a vertical axis, or track the sun on two axes. Fixed-tilt systems are widely used due to their lower cost. Single-axis systems provide higher energy but have slightly higher costs. Dual-axis systems are the most effective but have higher operation and maintenance (O&M) costs. The first type is stationary, while the other two are dynamic due to their sun-tracking ability [23,24]. Solar trackers provide financial and non-financial benefits. Financial benefits depend on the system's location and the tracker's expenses. Non-financial benefits include reduced PV panel usage and environmental impact. Single-axis trackers increase energy generation by 28.4%, while dual-axis trackers increase it by 40% but have higher costs and energy losses. Off-grid systems must be designed to generate enough power and have sufficient battery capacity. Complex systems may include solar-tracking, weather stations, and computing systems. Utility-scale installations may also include substations and transformer banks. Nearly 50% of utility-scale PV plants use single-axis trackers, increasing output power by 20% with less than a 10% cost increase [25–29]. The performance of a solar tracker is influenced by its configuration, climate conditions, and geographical location. While it can increase energy gain from PV modules in many situations, it may not be suitable for hot climates [30]. Therefore, a detailed analysis should be conducted before implementing a solar tracking system in any area.

The recently introduced technologies regarding renewable energies and optimization are presented in some works. To exemplify, Ebrahimi-Mogadam et al. investigated the design of a sustainable tri-generation system driven by biomass (MSW: municipal solid waste) externally fired gas turbine cycle and utilizing a double-effect absorption chiller/heater [31]. Kheir Abadi et al. investigated a hybrid solar/wind system proposed to satisfy the electrical and cooling demands and hot water consumption of a building. Cooling demand is covered by combining absorption and compression chillers; so that, the primary energy of the compression chiller is supplied by a wind turbine and photovoltaic (PV) panels, and the required thermal energy of the absorption chiller is supplied through evacuated tube collectors (ETCs) [32].

Alahmadi et al. compared the output power of the single-axis tracker without a tracker PV panel in Medina. The results showed a 22.5% increment in electricity production for the system including the single-axis tracker for the installed 270 W PV panels [33]. Bajawi et al. using PVsyst software reported an increment of 28% and 26% of power production in AlShuaiba and Al-Shuqiq, respectively, in the case of using a dual-axis tracker system compared to the non-tracker PV panels [34]. Additionally, results from Alabdali et al. and Alzahrani et al. regarding the use of a dual-axis tracker in Yanbu, Rabigh, Al-Riyadh, and Al-Jubail regions showed the same results [35,36]. Imam et al. investigated different PV panels for grid-connected HRES. The sensitivity indicates that the continuous two-axis tracking system outperforms the other tracking systems in terms of productivity, with an additional 35.2% annual energy production compared to the system fixed at an optimum tilt angle. Furthermore, adjustments to the monthly optimum tilt angle result in no significant production changes [37]. Al Garni et al. investigated a grid-connected PV panel in Makkah under different tracking systems. The results showed 0.044, 0.055, 0.45, and 0.053 (USD/kWh) of COE values for, fixed tilt without tracking, horizontal axis tracker, vertical axis tracker, and two-axis tracker, respectively [38].

Table 1. Some of the previous HRES studies related to the current study conducted in Saudi Arabia.

Location	Goal	System	COE (USD/kWh)	Year	Ref.
Al-Sulaymania	Optimization to loss of power supply and annualized system cost	PV/WT/Gen/Bat	0.093	2021	[4]
Baha University	Feasibility analysis of HRES to support the college's energy	PV/WT/FC/Bat	0.289	2020	[39]
Neom	Finding HRES with the minimum NPC	PV/WT/Gen/Bat	0.164	2019	[40]
Arar	Minimizing the COE and the loss of load probability	PV/WT/Gen/Bat	0.039	2021	[41]
Jubail	Technical and economic viability of various hybrid energy system designs is weighed	PV/WT/Gen/Bat	0.183 to 0.244	2019	[42]
Neom	Selection of best configuration to supply the load demand	PV/WT/Gen/Bat PV/Bat	0.375 0.501	2021	[43]
Ad Dulaymiyah	Finding the optimal component sizes and configurations to supply the load demand	PV/Bat	0.442	2021	[44]
Yanbu	Select the best microgrid configuration while minimizing both NPC and LCOE	PV/WT/Gen/Bat	0.341 to 0.386	2021	[45]
Aljouf	Determining the optimal sizing of the HRES	PV/WT/Gen/Bat	0.134	2020	[46]

In this study, up to the knowledge of the authors, for the first time, investigation of the performance of different tracker systems considering both technical and economic aspects in an off-grid PV/WT/Gen/Bat system in Saudi Arabia is conducted. In the simulation process, the effect of CO_2 social penalty is also considered to affect using free sizes of diesel generators due to the low cost of fuel.

The structure of the paper is as follows: in the methodology section, firstly, the description of the case study regions along with their resources are discussed and the corresponding assumption is presented. Then, the proposed configurations along with their equipment and the related technical and economic equations are presented. Furthermore, the main characteristics of the equipment are given. In the result and discussion section, the main and primary results of the simulation and optimum results are presented for each configuration. Then, the results of the sensitivity analyses are presented and discussed. Finally, in the conclusion section, the main concluded points based on the obtained results mentioned in the results and discussion section are presented.

2. Methodology

In the methodology section, first of all, the case study regions, including 7 locations and their conditions such as latitude (Lat), longitude (Long), wind speed, solar radiation, clearness index (CI), and annual average temperature (Temp) are presented to clarify the simulation which is conducted by HOMER software. Secondly, the proposed load demand that is constant for all locations is discussed. Then, the proposed 4 configurations: config 1 and config 2 include PV, wind turbine, diesel generator, and battery; config 3 includes PV and battery; and config 4 includes only a diesel generator are discussed. Finally, the selected items and their technical descriptions along with economic parameters are presented.

To model the configurations, economic parameters such as inflation rate and discount rate, and the cost of equipment are collected and entered into the software. According to the selected case study regions, the latitude and longitude of the locations are entered into the software, by which the resources such as wind speed, temperature, and solar irradiation can be automatically obtained through the HOMER software. Then, the proposed load demand is considered and according to the proposed configurations, the needed equipment is selected, and the associated costs are entered into the software. Setting the maximum simulations per optimization on 10,000, the system design precision at 0.01, focus factor at 50, and running the program, the optimum results can be obtained based on the lowest NPC values. Finally, some of the important sensitivity analyses are carried out, which are deeply discussed in Sections 3.5 and 3.6.

2.1. Case Study Regions

In this study, 7 case study regions with different weather conditions to cover various parts of Saudi Arabia are selected. These regions include Riyadh (Loc1), Eastern (Loc2), Al Jawf (Loc3), Tabuk (Loc4), Madinah (Loc5), Asir (Loc6), and Hail (Loc7). Figure 1 shows the selected locations along with their latitudes and longitudes. Loc1, Loc2, Loc3, and Loc7 are in the middle and eastern parts of the country, while Loc4, Loc5, and Loc6 are in the western part of the country as coastal regions adjacent to the Red Sea. Figure 2 shows the daily global horizontal irradiation (GHI) (kWh/m^2/day) heat map of solar radiation in Saudi Arabia. As can be seen, this country has a high GHI that is appropriate for installing PV panels. The selected locations include various ranges of GHIs, with values ranging between 5.82 to 6.39 kWh/m^2/day. Figure 3 shows the heat map of wind speed in Saudi Arabia. According to this figure, most parts of the country have a wind speed between 5 to 8 m/s which is appropriate for power production from wind turbines. The selected locations have a wind speed between 4.28 to 7.21 m/s. The reported numbers in Figures 2 and 3 are based on heat maps according to the wind and solar atlas. The values for wind and GHI used in simulations are based on NASA reports as presented in Table 2.

Figure 1. The selected case study locations in Saudi Arabia.

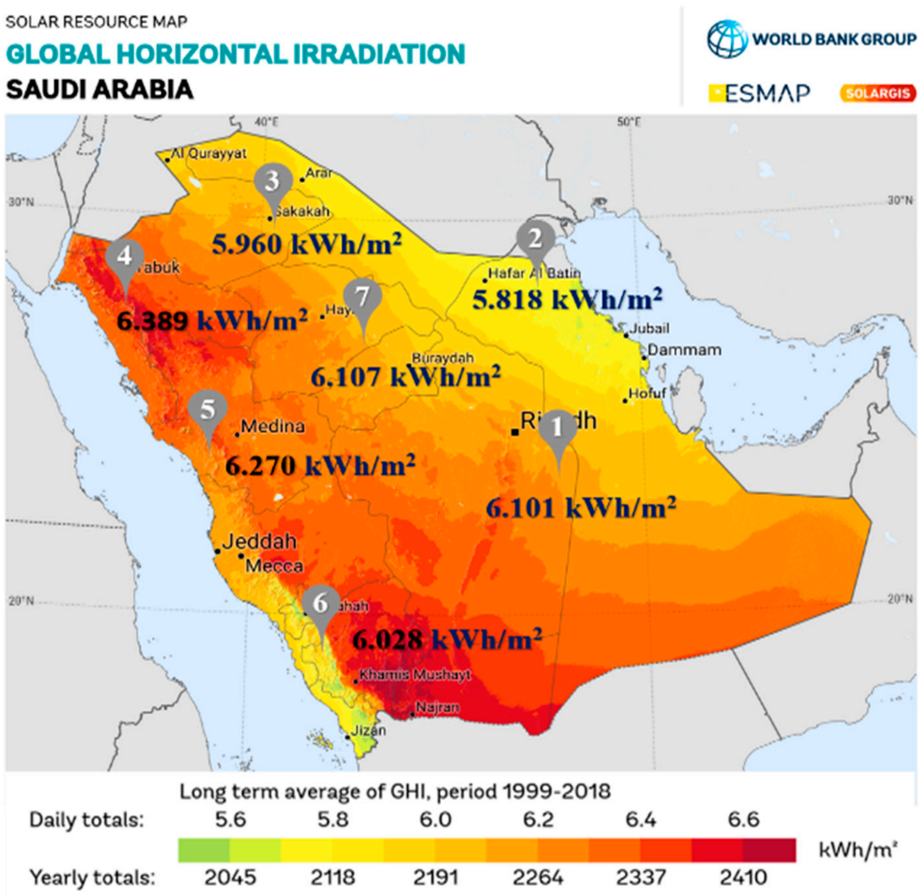


Figure 2. The solar GHI heat map of Saudi Arabia.

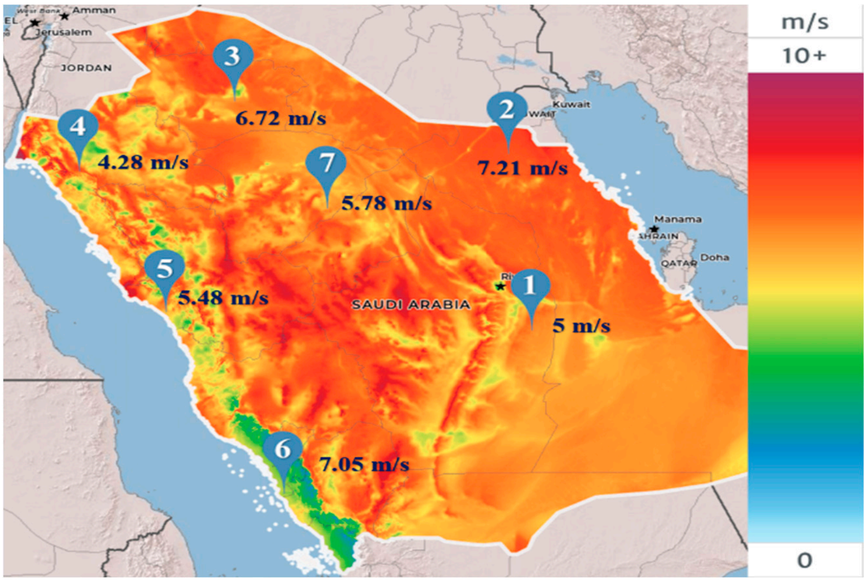


Figure 3. The wind speed heat map of Saudi Arabia.

Table 2. GHI (kWh/m^2·day), wind speed (m/s), CI, and air temperature (°C) for the selected locations.

	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	CI	0.56	0.59	0.58	0.59	0.65	0.71	0.69	0.68	0.67	0.66	0.60	0.54
Loc1	GHI	3.81	4.69	5.37	6.18	7.17	7.89	7.59	7.20	6.47	5.50	4.25	3.51
	Wind Speed	5.49	5.92	5.96	5.67	5.45	6.24	6.38	5.70	5.06	4.77	5.06	5.21
	CI	0.53	0.59	0.58	0.58	0.65	0.70	0.69	0.69	0.67	0.63	0.53	0.48
Loc2	GHI	3.30	4.31	5.18	6.00	7.16	7.91	7.71	7.31	6.28	4.92	3.42	2.77
	Wind Speed	5.45	5.87	5.99	5.94	6.10	7.38	7.44	6.47	5.75	5.50	5.45	5.40
	CI	0.52	0.57	0.61	0.64	0.66	0.74	0.72	0.71	0.70	0.61	0.55	0.50
Loc3	GHI	3.02	4.07	5.30	6.57	7.37	8.41	8.08	7.45	6.39	4.59	3.33	2.70
	Wind Speed	5.23	5.77	5.90	5.76	5.62	5.61	5.91	5.11	4.86	5.13	5.04	5.04
	CI	0.62	0.65	0.65	0.65	0.66	0.71	0.70	0.68	0.67	0.62	0.62	0.61
Loc4	GHI	3.84	4.80	5.81	6.67	7.30	8.02	7.82	7.20	6.26	4.87	3.96	3.51
	Wind Speed	5.28	5.46	5.64	5.55	5.38	5.44	4.97	4.86	4.95	4.70	5.05	5.13
	CI	0.68	0.70	0.69	0.70	0.67	0.70	0.69	0.67	0.66	0.69	0.68	0.67
Loc5	GHI	4.67	5.60	6.46	7.26	7.39	7.86	7.67	7.07	6.43	5.74	4.87	4.36
	Wind Speed	4.98	4.82	4.78	4.35	4.26	4.49	4.17	4.08	4.12	3.96	4.24	4.68
	CI	0.59	0.62	0.62	0.63	0.63	0.64	0.62	0.59	0.62	0.67	0.62	0.59
Loc6	GHI	4.39	5.20	5.95	6.60	6.85	7.08	6.81	6.22	6.09	5.84	4.76	4.23
	Wind Speed	4.55	4.54	4.64	4.25	3.71	3.88	3.88	3.41	3.64	4.47	4.26	4.34
	CI	0.58	0.62	0.59	0.59	0.62	0.69	0.69	0.67	0.65	0.61	0.55	0.55
Loc7	GHI	3.72	4.64	5.34	6.13	6.85	7.85	7.67	7.07	6.13	4.82	3.63	3.31
	Wind Speed	5.81	6.17	6.14	5.86	5.65	5.74	5.83	5.32	5.16	5.58	5.76	5.75
Annual average		**Loc1**	**Loc2**	**Loc3**	**Loc4**	**Loc5**	**Loc6**	**Loc7**					
Wind speed		5.58	6.06	5.42	5.2	4.41	4.13	5.73					
GHI		5.8	6	5.61	5.84	6.28	5.84	6					
Temp		25.75	24.74	21.29	20.33	28.12	24.56	22.63					

Table 2 presents the monthly average clearness index, CI, GHI, and wind speed for the selected locations, along with their annual average values. Considering the heat maps in Figures 2 and 3 that show GHI and wind speed in Saudi Arabia, GHIs of 5.8 to 6.28 kWh/m^2/day and wind speeds of 4.13 to 6.06 m/s can be good ranges for investigating PV and wind turbine power production in the country.

The building sector is responsible for almost 80% of electrical energy consumption in the country, with over 50% attributed to residential buildings [47]. Air conditioning in

Saudi Arabia uses a high amount of electricity in the residential sector. This consumption, especially in warm months, can affect the size of renewable components during the design step since the design usually aims to fulfill the peak load. Figure 4 illustrates the load demand proposed for all locations where the usage is residential. According to this figure, load demand in June, July, and August is high due to air conditioning needs. In March, April, and September it is medium, and for the rest of the year, it is relatively low. The scaled annual average of load demand is considered to be 988.97 kWh/day and the peak load is 212.34 kW.

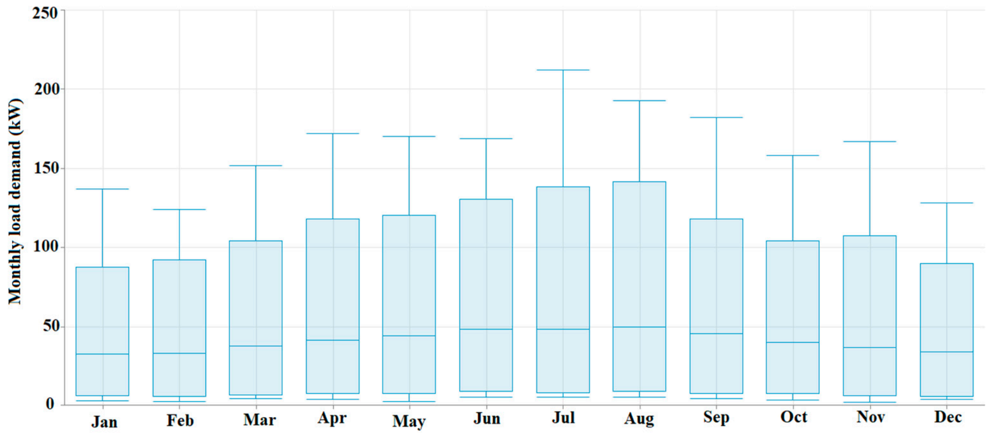


Figure 4. The proposed load demand for the selected locations.

2.2. Assumptions

The inflation rate, discount rate, and project lifetime are proposed at 2% [48], 5% [24], and 20 years, respectively. The annual capacity shortage, which indicates the allowable percentage of not providing electricity demand in the optimization process, is considered to be 1%. The optimization is conducted under cycle charging, load following, and combined dispatch strategies. Random variability of load demand for day (da)-to-day changes is considered to be 10%, and the timestep factor that shows possible changes at a specific hour from one day to another is considered to be 20%. Finally, the social cost of CO_2 emission is considered to be USD 16/ton CO_2 [24].

2.3. Configurations and Components

The proposed configurations are presented in Table 3. For PV panels in each location, the configuration is considered to include PV panels without a tracker (NT), PV panels with a vertical axis continuous adjustment tracker, PV panels with a horizontal axis continuous adjustment tracker (HT), and PV panels with a dual-axis continuous adjustment tracker (DT). Config 1 includes PV, wind turbine, generator, and battery. In this config, the possible optimum systems for the selected locations are presented along with the components' capacities. Config 2 is the same as config 1, but 100 kW PV is considered constant since in some cases there may be a limitation of land for installing PV panels. Additionally, considering a constant value for PV makes it possible to see the performance of PV panels and tracker systems in different locations. In the case of using other power producers and configurations, the performance of 100 kW PV would be the same. Config 3 aims to find the size of PV panels under different tracker systems to reach the load demand in each location (988.97 kWh/day and a peak load of 212.34 kW). Most of the remote sites in Saudi Arabia depend on fossil fuel-based energy producers such as diesel generators where the availability of the fuel and low efficiencies along with pollution are the main concerns of these kinds of systems [24]. In this respect, Config 4 includes diesel generators to supply load demand. The goal is to see the amount of pollutant emissions where there is no renewable system. This config would be valuable for comparing CO_2 emissions in fossil fuel-based systems and hybrid renewable energy systems.

Table 3. The proposed configurations.

Options	PV	Wind	Gen	Bat	Constraints	Sensitivity	
						PV Initial Cost (USD)	GHI (kWh/m^2/da)
Config 1	✓	✓	✓	✓			
Config 2	✓	✓	✓	✓	100 kW PV		
Config 3	✓			✓			
Config 4			✓				
Sens 1	✓	✓	✓	✓	100 kW PV	Multiplied by 0.7 to 1.4	
Sens 2	✓	✓	✓	✓	100 kW PV		From 3.5 to 6.5

In Sens 1, a sensitivity analysis is carried out on the initial cost of PV where the system includes 100 kW PV. The capital cost is multiplied by 0.7 to 1.4. This can also be considered as tracker system cost changes where the capital cost of PV is constant. This sensitivity analysis is conducted to see the effect of PV costs on the COE values of the proposed tracker systems and to find the cost-effective tracker system for each location. Finally, a sensitivity analysis named Sens 2 with 100 kW PV on GHI values between 3.5 to 6.5 will show the effect of GHI on COE and the cost-effective tracker system under different GHIs. The schematic view of the configuration is presented in Figure 5.

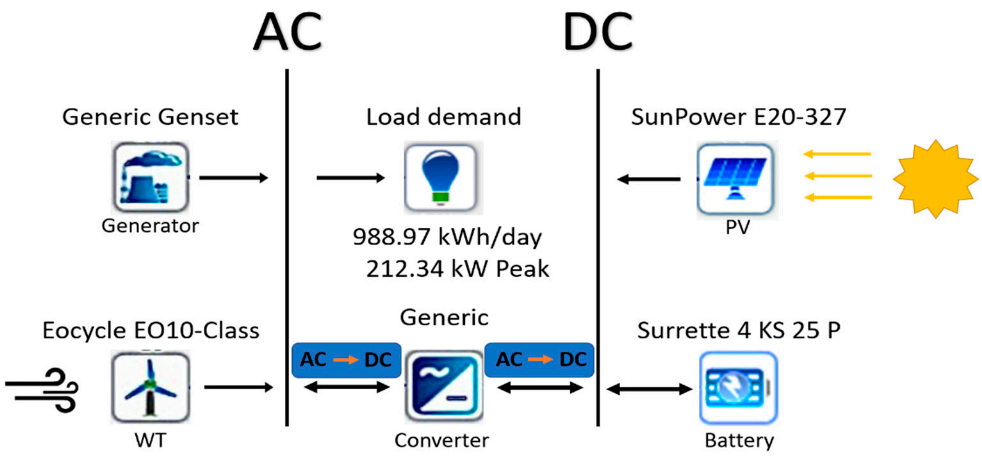


Figure 5. Schematic view of the proposed system.

The selected components, including PV, wind turbine, generator, battery, and converter (Con), and their specifications are reported in Table 4. The selection criteria follow previous studies in Saudi Arabia. A flat plate PV panel named SunPower E20-327 produces electricity from solar rays. Equation (1), which is used to calculate power production from PV panels, is based on equations from hybrid optimization model for multiple energy resources (HOMER) software.

$$\text{Power production from PV panels} = \text{Rated Capacity} * \text{DF} * \left(\frac{\text{SRI}}{\text{IR}}\right) * [1 + \text{TCP} * (\text{CT} - \text{CT}_{\text{STC}})] \quad (1)$$

where the rated capacity (kW) of PV is generated power under standard test conditions (STC) for the radiation of 1 kW/m^2 and cell temperature of 25 °C. Derating factor (DF) (%) represents the reduction of power production along the PV's lifetime. Solar radiation incident (SRI) (kW/m^2) in the current time step while irradiation (IR) (1 kW/m^2) is the incident radiation at STC. TCP is the temperature coefficient of power (%/°C) as a dependency of power output on the cell temperature. CT and CT_{STC} are PV's cell temperatures (°C) at reality and STC, respectively [49].

Table 4. Technical specifications of the selected components.

Item	Characteristics	Value	Item	Characteristics	Value
PV	Model name	SunPower E20-327	Bat	Model name	Surrette 4 KS 25P
	Panel type	Flat plate		Capacity	7.55 (kWh)
	Nominal capacity	0.327 (kW)		Voltage	4 (V)
	Temperature coefficient	−0.38		Current	459 (A)
	Operating temperature	45 °C		Efficiency	80 (%)
	Efficiency at STC	20.4 (%)	Gen	Model name	Generic Genset
	Derating factor	88 (%)		Capacity (kW)	1 (kW)
WT	Model name	Eocycle EO10-Class III		Min load ratio (%)	25 (%)
	Rated capacity	10 (kW)		Fuel	Diesel
	Cut in/off wind speed	2.75–20 (m/s)		Fuel price	0.25 (USD/L)
	Hub height	16 (m)	Con	Model	Generic
	Rotor diameter	15.81 (m)		Efficiency (%)	95 (%)

The selected wind turbine in this study is Eocycle EO10-Class III to convert wind to electricity. The output of the wind turbine can be obtained based on the following equations [50]:

$$P_{WT} = \begin{cases} 0 \quad U < U_{Cutin} \\ m \cdot U^3 - n \cdot P_{rated} \quad U_{Cutin} < U < U_{rated} \\ P_{rated} \quad U_{rated} < U < U_{Cutoff} \\ 0 \quad U > U_{Cutoff} \end{cases} \tag{2}$$

where P_{rated} is the rated power and U_{rated} is the rated wind speed. m and n parameters can be obtained by Equation (3) and Equation (4), respectively.

$$m = \frac{P_{rated}}{U_{rated}^3 - U_{Cutin}^3} \tag{3}$$

$$n = \frac{V_{Cutin}^3}{U_{rated}^3 - U_{Cutin}^3} \tag{4}$$

Generated effective power obtained from a WT would be as Equation (5)

$$P_{e.w} = P_w.A_w.\eta_w \tag{5}$$

where A_w is the total swept and η_w is the efficiency of the WT.

Additionally, the output power of the wind turbine can be calculated as Equation (6) [51]

$$P_{WT} = \left(\frac{\rho}{\rho_0}\right).P_{WT.STP}(6) \tag{6}$$

where ρ is the real air density, ρ_0 is the air density at standard conditions, and $P_{WT.STP}$ is the output of the wind turbine using the turbine's power curve.

In the following, the most important economic parameters used in this research are presented:

NPC is the total expenses of purchase, installation, and O&M of components, along with other related costs such as emission penalties minus salvage which is the revenues gained through the project's lifetime as in Equation (7) [52].

$$\mathrm{NPC} = \frac{C_i + C_m + C_r - S}{\mathrm{CRF}(i, n)} \tag{7}$$

where C_i is the initial cost, including purchase and installation, C_m is maintenance expenses, C_r is the replacement cost of new components, S presents the salvage, and CRF is determined as the capital recovery factor.

Cost of energy indicates the cost of useful obtained energy per amount of obtained electricity (kWh) as a most important factor for the economic evaluation of the system. From Equation (8), COE is denoted [53]:

$$COE = \frac{C_{ann.tot}}{E_{served}} \quad (8)$$

where $C_{ann.tot}$ and E_{served} are annual expenses for energy production and served electricity, respectively.

Battery packs would be useful for supporting load demand, especially at night when there is no solar radiation or when there is no suitable wind speed within the cut-off/in range. The size of the components in the optimum HRESs is calculated based on peak load. As a result, the components produce excess electricity (Ee) at non-peak hours. A lead acid battery named Surrette 4 KS 25P is used to store excess electricity generated by PV and wind turbines. A generic Genset diesel generator is used as a backup component to support the needed power when PV and wind turbines cannot fulfill the load demand. A converter is used in the configuration to convert DC and AC loads to each other. The characteristics and expenses of the components are presented in Tables 4 and 5, respectively.

Table 5. Economic parameters of the selected components based on the reported costs [16,42–44].

Module	Lifetime	Capital Cost	Replacement	Maintenance
PV	20 yr	1300 (USD/kW)	1300 (USD/kW)	10 (USD/kW/yr)
WT	20 yr	3000 (USD/kW)	3000 (USD/kW)	600 (USD/kW/yr)
Gen	15,000 h	450 (USD/kW)	450 (USD/kW)	0.018 (USD/op·h)
Bat	20 yr	1150 (USD/Qnt)	900 (USD/Qnt)	40 (USD/Qnt/yr)
Con	15 yr	300 (USD/kW)	300 (USD/kW)	3 (USD/yr·kW)
VT	20 yr	300 (USD/kW)	300 (USD/kW)	
HT	20 yr	300 (USD/kW)	300 (USD/kW)	
DT	20 yr	500 (USD/kW)	500(USD/kW)	

3. Results and Discussion

To investigate the economic and environmental outputs obtained from the HOMER software, the results of the optimization are discussed in this section. All economic input parameters for the simulations are considered the same. The results are reported based on the different configurations mentioned in Table 3. For each location, 4 configurations are proposed: config 1, config 2, config 3, and config 4. In each configuration, four different states of using PV panels are proposed: without a tracker (NT), with a vertical axis continuous adjustment tracker, with a horizontal axis continuous adjustment tracker (HT), and with a dual-axis continuous adjustment tracker (DT). Finally, two separate sensitivity analyses (Sens 1 and Sens 2) are carried out for systems restricted to using 100 kW PV.

- The results of config 1 are presented as optimal to see the optimal sizing of the components where there is no imposed restriction on the configuration related to using specific components.
- The results of config 2 are presented as 100 kW PV constant, where the size of PV panels in each simulation is considered to be 100 kW. This allows us to see the economic results of the optimization for different tracker systems.
- The results of config 3 are presented as 100% PV to reach the load. This allows us to see how much PV panels under different tracking systems can fulfill the load demand.
- The results of config 4 are presented as 100% Gen to see how much CO_2 emission will be emitted where there is no renewable energy producer.
- The results of the sensitivity analysis on the capital cost of PV and the amount of solar GHI where the systems use 100 kW PV are presented in a different section. This allows us to see the influence of changing the capital cost of PV panels or tracker systems and GHI on the COEs for each tracker system.

The results of config 1, config 2, and config 3 are presented in Table 6.

Table 6. The results of config 1, config 2, and config 3.

	PV (kW)	Wind (Qnt)	Gen (kW)	Bat (Qnt)	Con (kW)	NPC (USD)	COE (USD/kWh)	100 kW PV Production (kWh/yr)	COE of 100 kW PV (USD/kWh)	PV to Reach to LOAD (kW)	NPC to Reach to Load (MUSD)
	Config 1							Config 2		Config 3	
Loc1											
NT	33	6	80	57	35	635,429	0.12	181,938	0.124	292	1.19
VT	42	5	80	55	40	632,098	0.117	221,860	0.124	268	1.19
HT	27	6	80	49	37	641,363	0.119	197,040	0.127	293	1.24
DT	38	5	80	58	39	631,343	0.117	246,087	0.127	239	1.23
Loc2											
NT	12	6	80	38	33	582,611	0.108	175,417	0.117	388	1.32
VT	23	6	60	49	74	580,814	0.108	218,231	0.119	345	1.37
HT	0	7	70	41	46	583,243	0.108	190,390	0.121	380	1.42
DT	21	6	70	51	45	581,339	0.108	236,813	0.122	322	1.48
Loc3											
NT	31	6	80	55	40	647,285	0.12	181,869	0.125	369	1.31
VT	40	6	80	55	37	641,062	0.119	231,362	0.124	344	1.37
HT	30	6	80	47	39	652,672	0.121	198,197	0.128	353	1.41
DT	46	5	80	59	40	639,005	0.119	250,148	0.127	327	1.46
Loc4											
NT	54	5	80	59	42	661,349	0.123	193,297	0.126	331	1.14
VT	53	5	70	46	67	654,029	0.122	239,509	0.125	264	1.13
HT	50	5	80	62	43	668,924	0.124	209,574	0.129	249	1.19
DT	47	5	80	56	41	650,629	0.121	262,266	0.128	238	1.16
Loc5											
NT	94	4	70	64	69	745,896	0.139	198,390	0.139	296	1.11
VT	78	4	70	62	67	724,888	0.135	242,464	0.136	255	1.05
HT	86	4	70	65	66	753,065	0.14	215,999	0.141	276	1.12
DT	71	4	70	58	68	722,480	0.134	272,082	0.136	267	1.10
Loc6											
NT	78	5	80	76	49	759,981	0.141	183,208	0.142	346	1.23
VT	71	4	80	77	51	749,617	0.139	216,794	0.14	290	1.23
HT	71	5	80	73	49	771,475	0.143	197,770	0.145	305	1.28
DT	71	4	80	77	51	745,924	0.139	244,609	0.141	245	1.27
Loc7											
NT	37	6	80	57	36	624,767	0.116	181,684	0.122	331	1.24
VT	51	5	80	54	39	619,419	0.115	223,195	0.122	293	1.25
HT	19	6	80	46	36	624,542	0.116	196,435	0.125	319	1.32
DT	26	6	80	48	38	620,620	0.115	243,815	0.125	285	1.30

3.1. The Results of the Config 1

The results of the obtained optimum systems where there is no limitation on using the components are presented in Table 6. In this config for each location, only the tracker of the PV panel and its price are changed. As can be seen in the table, in all locations, the optimized HRES includes PV, WT, Gen, and Bat. Under this configuration, two types of analysis can be conducted: firstly, a comparison between the size of PV panels and secondly, a comparison between the COEs.

In Loc1, VT and DT have the lowest COEs, and NT is followed by HT. This means that VT and DT are more economic trackers compared to NT and DT. While considering the size of PV panels, since HT uses fewer PV panels, it needs less land or roof space for installation. In Loc2, the obtained values of COEs are the same while in the case of using HT, no PV panel will be used in the optimum system. This means that HT is not a suitable tracker for Loc2. In this location, VT uses the highest amount of PV panels compared to other trackers. In Loc3, VT and DT have the lowest COEs while NT and HT have the lowest amount of PV panels. In Loc4, the lowest amounts of COE and PV belong to DT. This means that in the case of using DT in Loc4, less space is needed, and COE shows more economic value. The same results as Loc4 can be inferred from the data related to Loc5. In Loc6, VT and DT would be better choices due to their lowest COE and PV. In Loc7, VT and DT are more economical while HT has the lowest PV.

As can be seen, the type of appropriate tracker differs from location to location when economic analysis is considered. Almost similar results can be inferred when environmental concerns are considered. In this regard, the RF and emitted CO_2 values in the case of using different tracker systems are illustrated in Figure 6. Considering CO_2 values in Loc1, NT, and DT are more environmentally friendly. Considering the economic comparison in the last paragraph, DT would be a good choice. From the same evaluation, VT, VT, DT, DT, DT, and VT are appropriate trackers for Loc2, Loc3, Loc4, Loc5, Loc6, and Loc7, respectively.

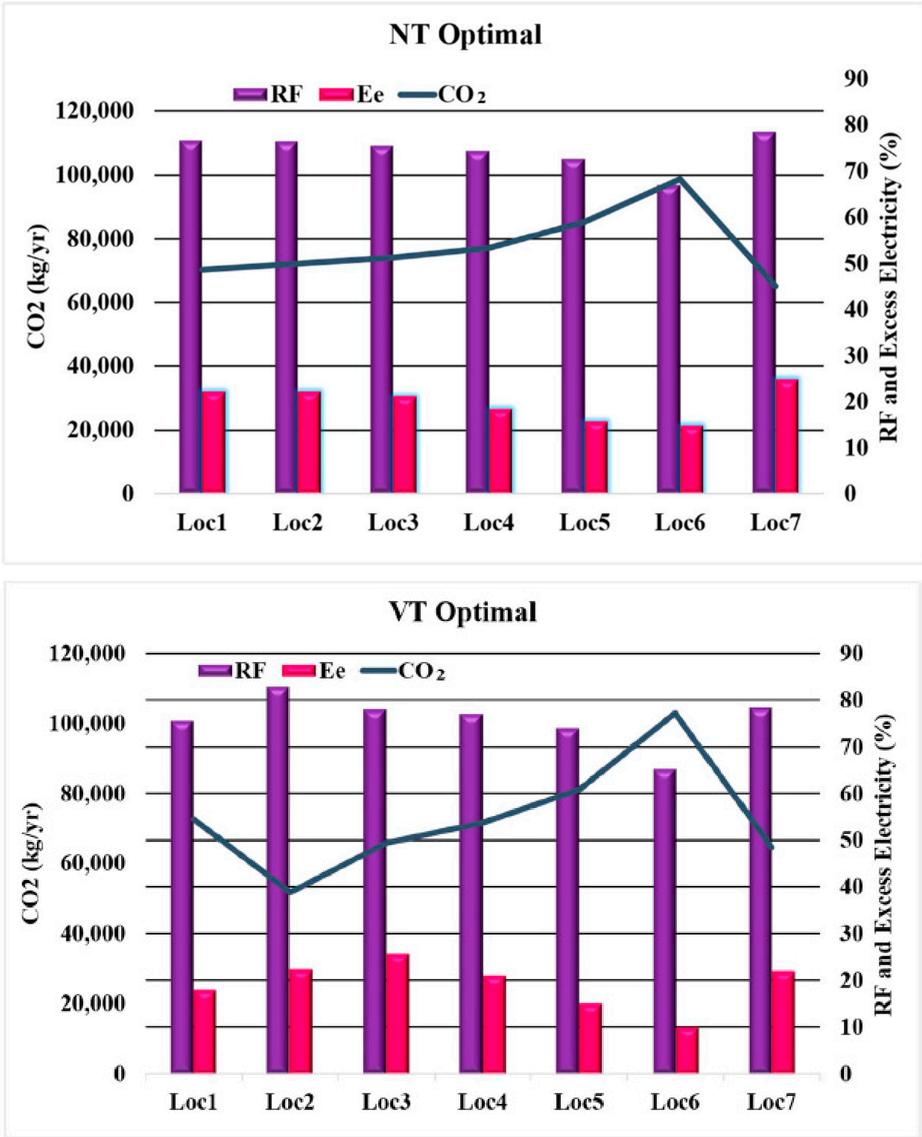


Figure 6. *Cont.*

Figure 6. RF and CO_2 emissions of optimized HRES under config 1.

Figure 7 shows PV production in the case of using different tracking systems. Since power production is almost equal in Loc5, it can be useful for comparing the size of PV panels. NT, VT, HT, and DT use 94, 78, 86, and 71 kW panels, respectively. This shows that for almost equal power production in Loc5, DT uses fewer panels and NT needs the highest amount of PV panels. To have a more exact analysis, in the case of using fewer PV panels including DT and VT, power production would be more compared to when using PV panels with NT and HT.

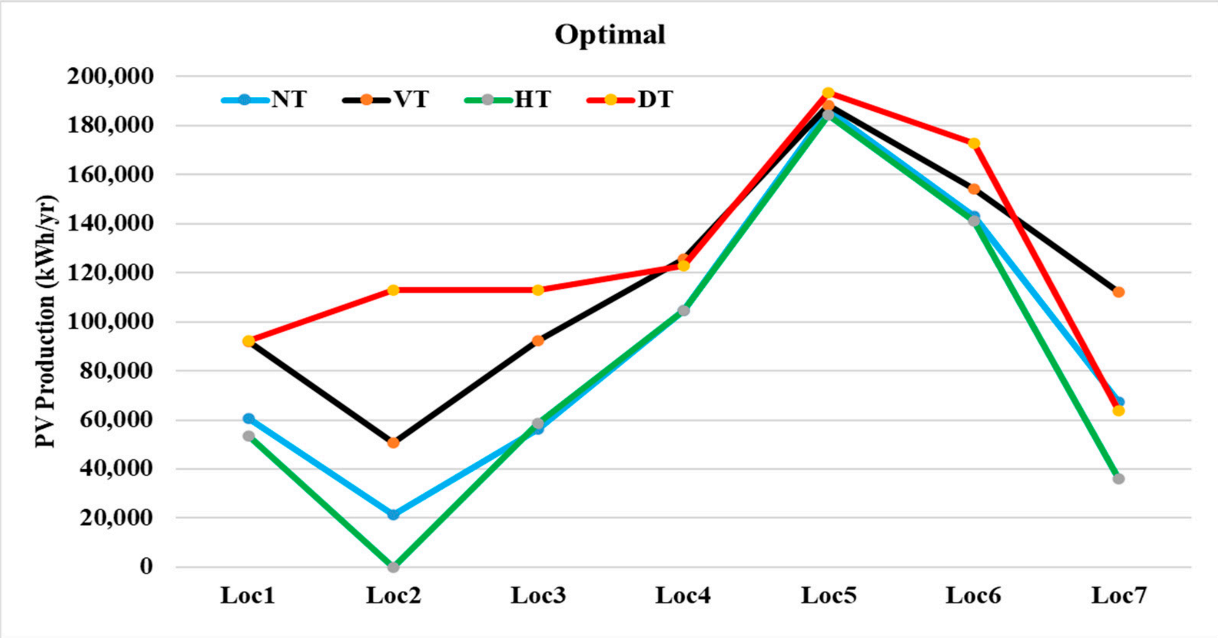


Figure 7. PV production under config 1.

Figure 8 shows the size of the components along with net present cost (NPC) and COE under different tracking systems for seven locations. As can be seen, the size of the components varies from location to location due to different wind speeds and solar GHIs. When PV panels have no tracker system (NT) or have VT or DT, based on the optimization results, Loc2 needs the least PV panels and wind turbines compensate for securing load demand. Loc5 needs the most PV panels and the least WTs in which WTs compensate for securing load demand. When HT is used, Loc7 needs the least amount of PV panels and again Loc5 needs the highest value of PV panels.

In the case of using each of NT, VT, HT, and DT, COEs in Loc5 and Loc6 are higher than in other locations and COE in Loc2 is the least. This means that under the same economic conditions and the same components, the price of electricity production from HRES in Loc2 is less than in other sites and the price of electricity production from HRES in Loc5 and Loc6 is higher than in other sites. Overall, considering the wind speed and solar GHI of Loc6, it is obvious that they have lower values compared to other sites in the country, resulting in lower RFs in HRES. When RF is low, HRES must use a diesel generator to supply load demand. Due to fuel prices and imposing a social penalty for CO_2, the price of electricity production rises in this location.

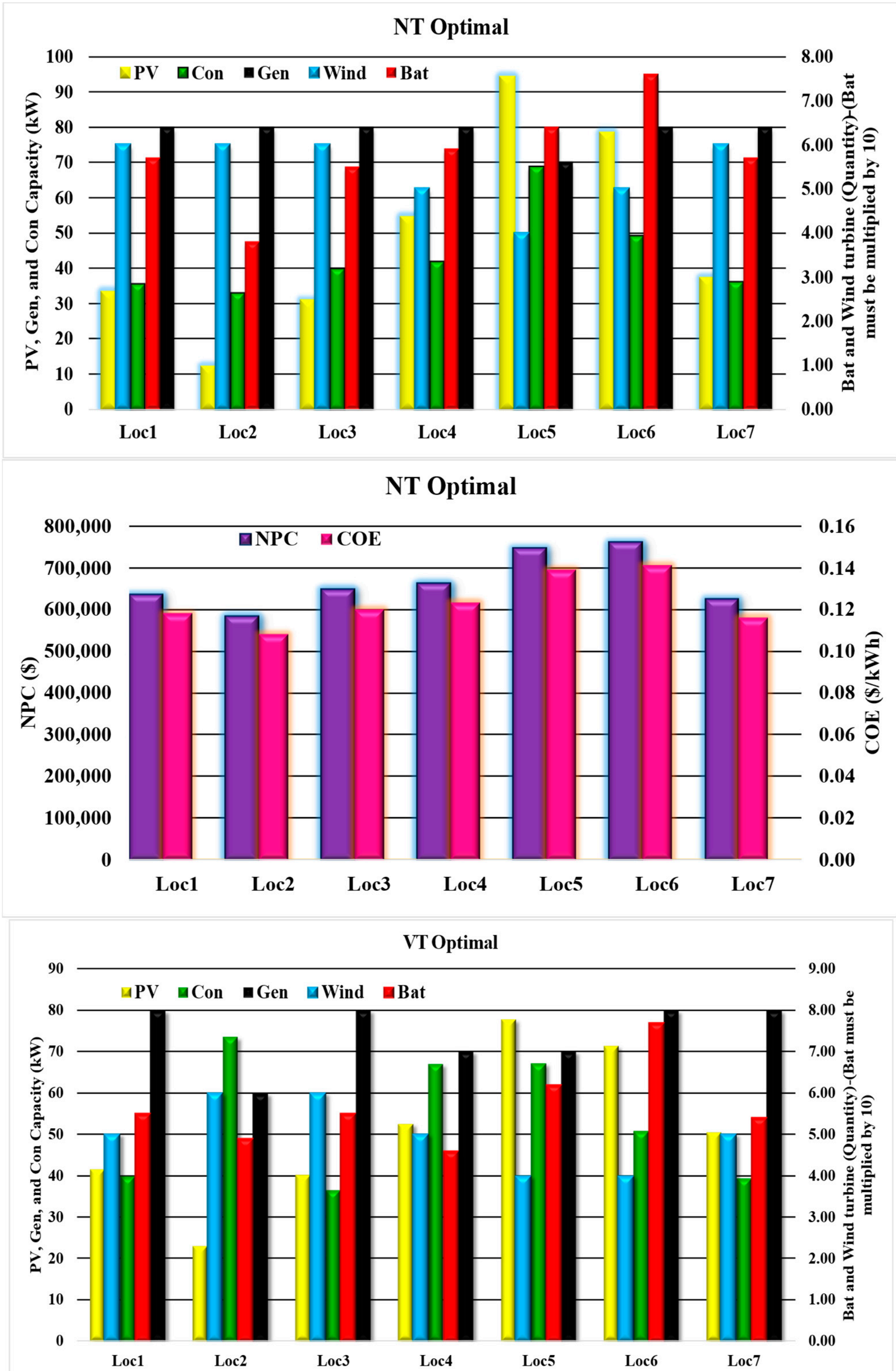


Figure 8. *Cont.*

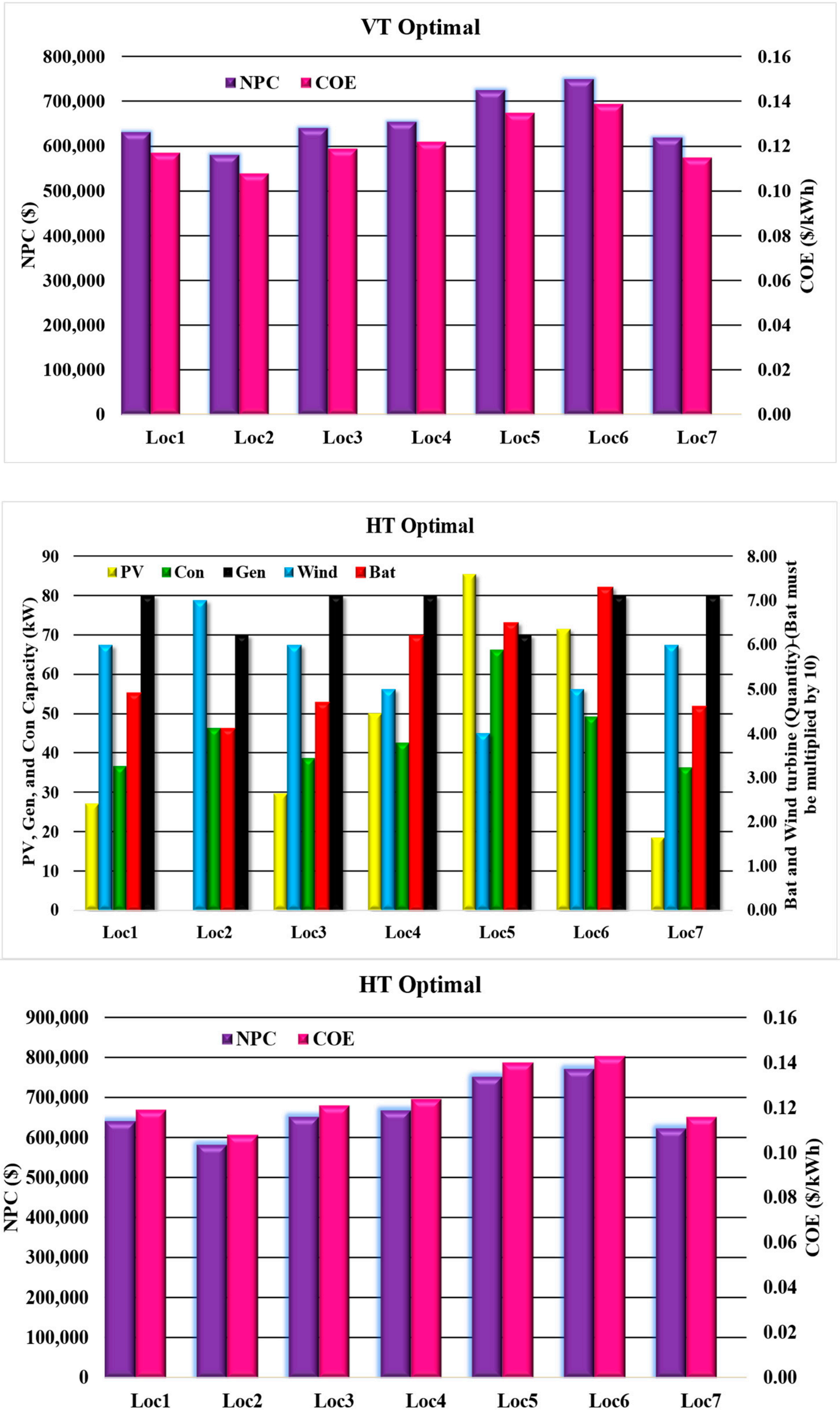


Figure 8. *Cont.*

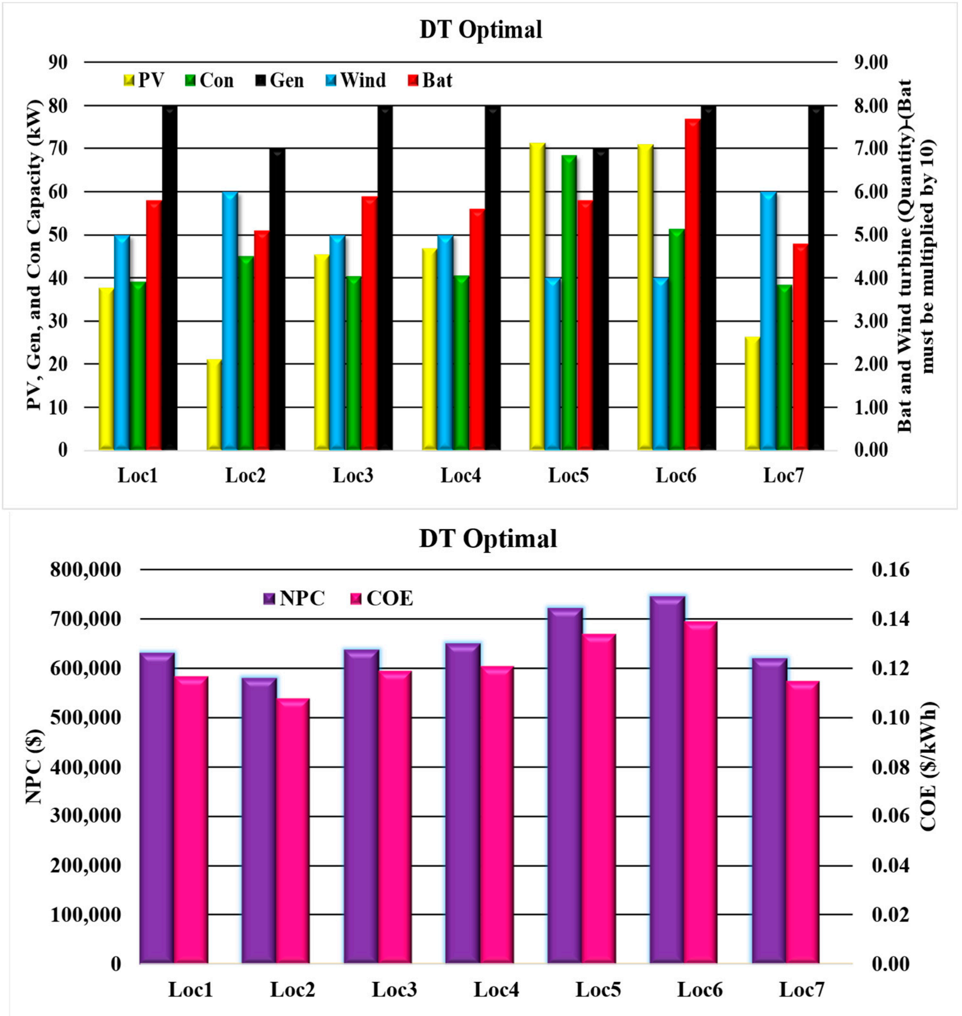


Figure 8. NPC, COE, and the size of the components under config 1.

3.2. The Results of the Config 2

In config 2, a 100 kW PV panel is used in all locations for each of NT, VT, HT, and DT. The obtained results are reported in Table 6. Figure 9 also shows the generation of electricity while using different tracker systems. As can be seen, DT, VT, HT, and NT produce the highest to the lowest amount of electricity. To see the rate of PV annual costs per produced electricity (USD/kWh), the levelized cost of energy (LCOE) is shown in Figure 9. It is obvious that HT has the highest LCOE for all locations and is not economic. According to this figure and considering both LCOE and PV productions, DT, VT, VT, VT, DT, NT, and VT are good choices as tracker systems in Loc1, Loc2 Loc3, Loc4, Loc5, Loc6, and Loc7, respectively.

3.3. The Results of the Config 3

To supply the demand load with PV panels, WT and Gen are removed in this configuration. This configuration shows how many PV panels each location needs to reach load demand. The needed size of the PV panels and their corresponding NPC values are presented in Table 6. Figure 10 also shows the amount of PV, Con, Bat, and corresponding COEs for each location. According to this figure and by comparing COEs while considering the size of the panels, VT, NT, NT, VT, VT, NT, and NT are, respectively, good choices in Loc1, Loc2 Loc3, Loc4, Loc5, Loc6, and Loc7 for installing PV modules in case of using 100% PV panel to supply load demand in the selected locations.

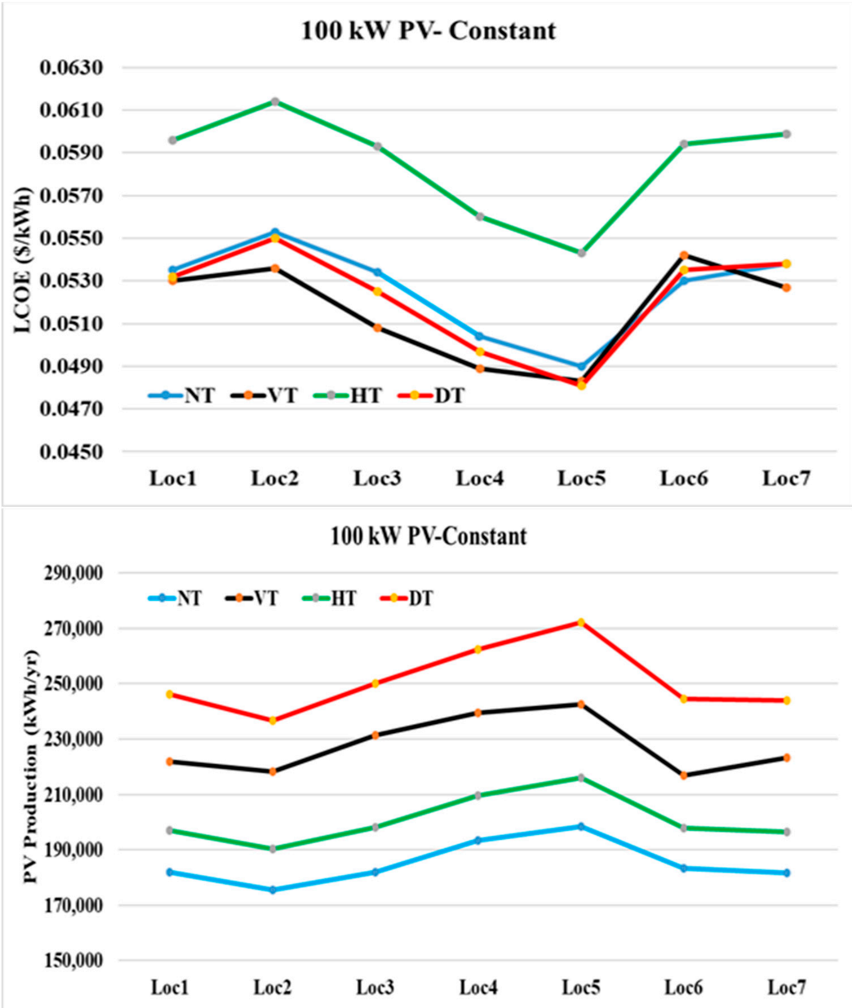
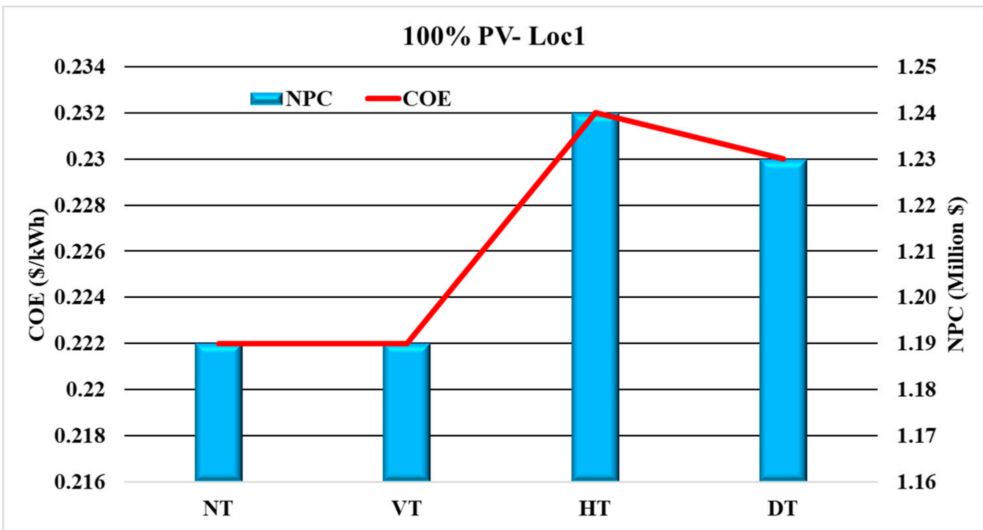


Figure 9. LCOE and PV production under config 2.



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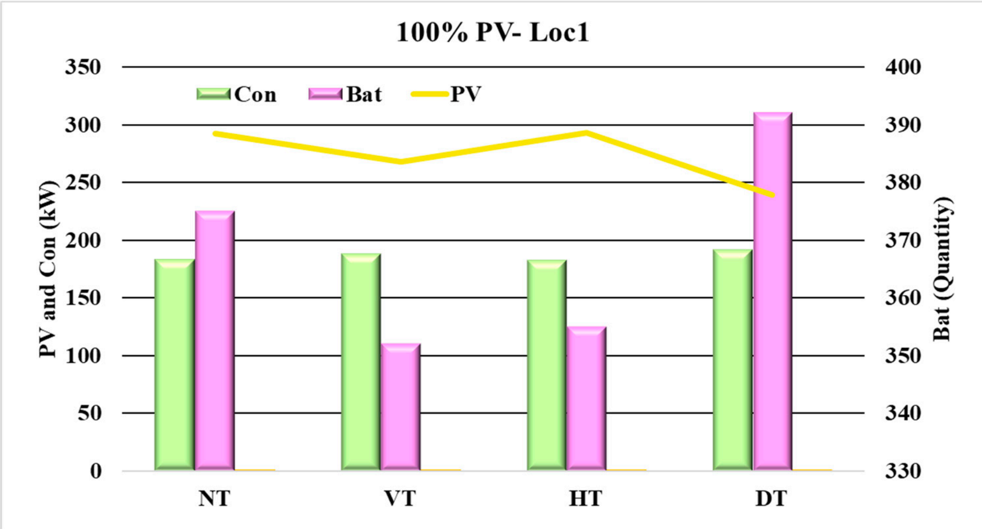

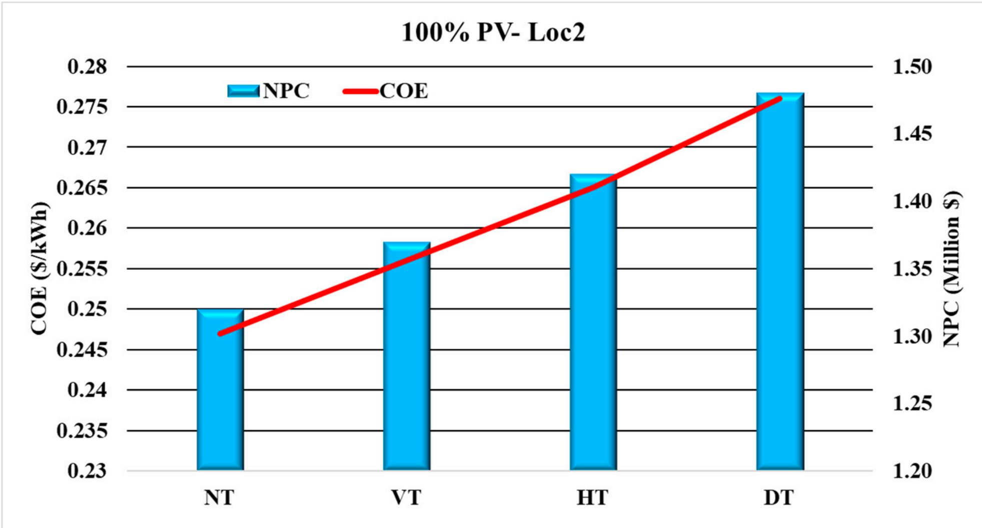

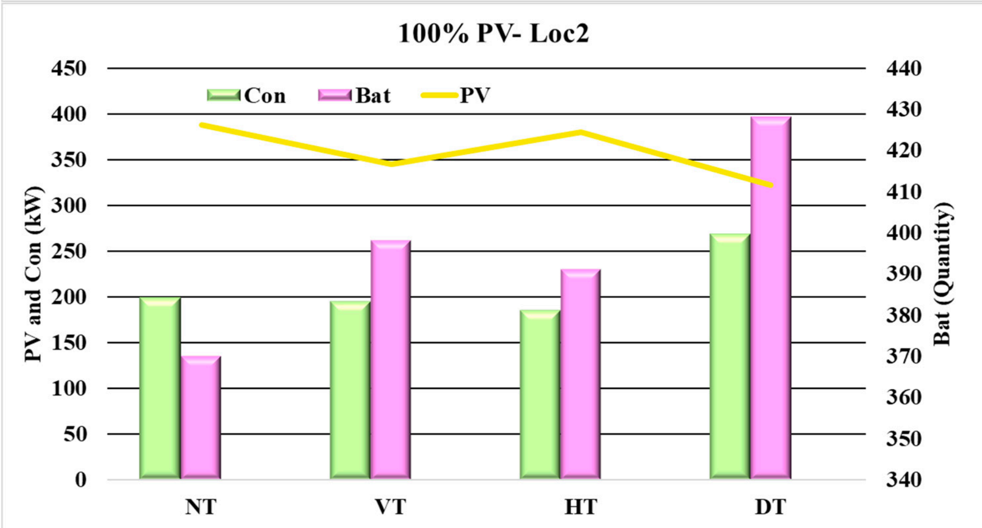

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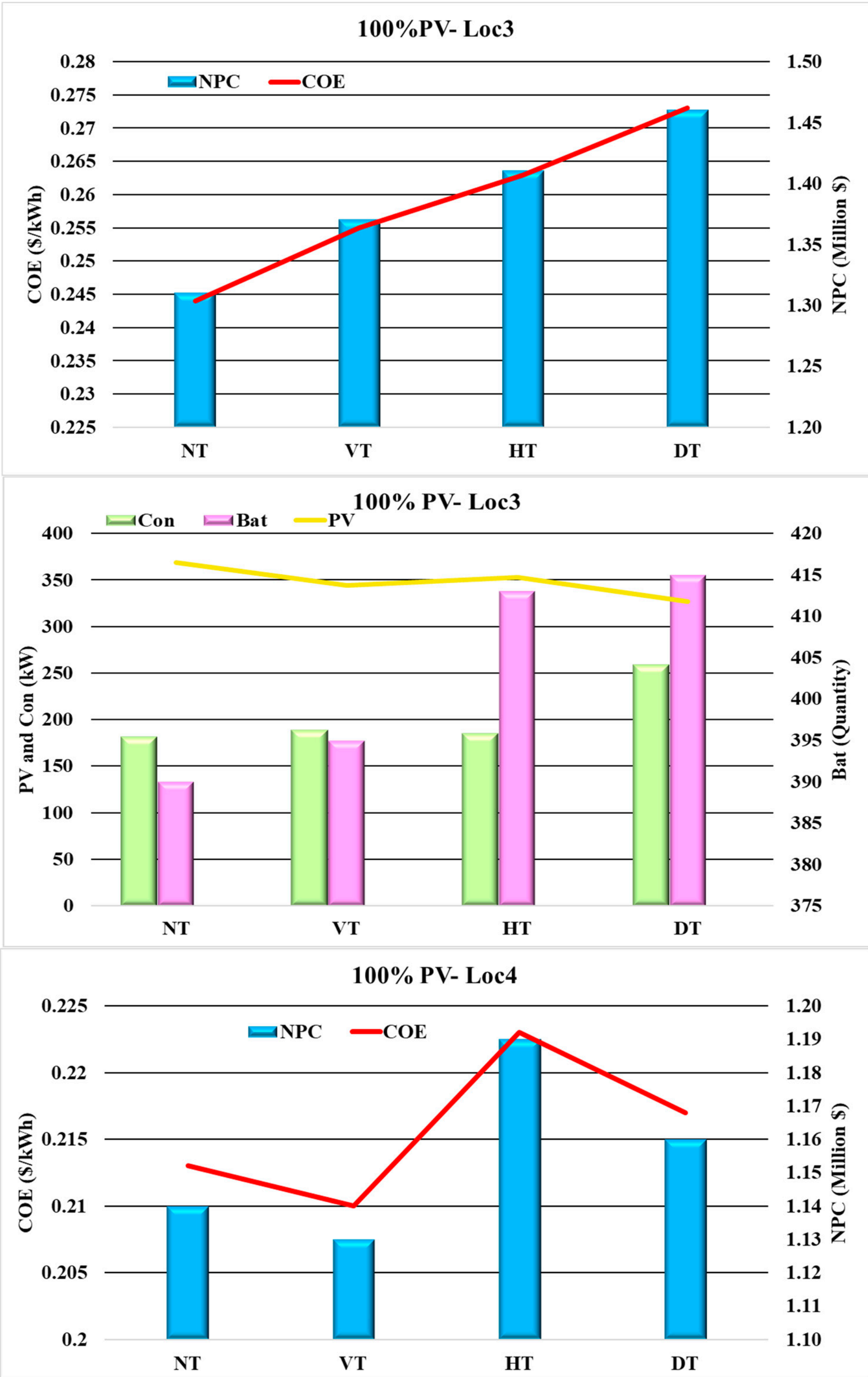

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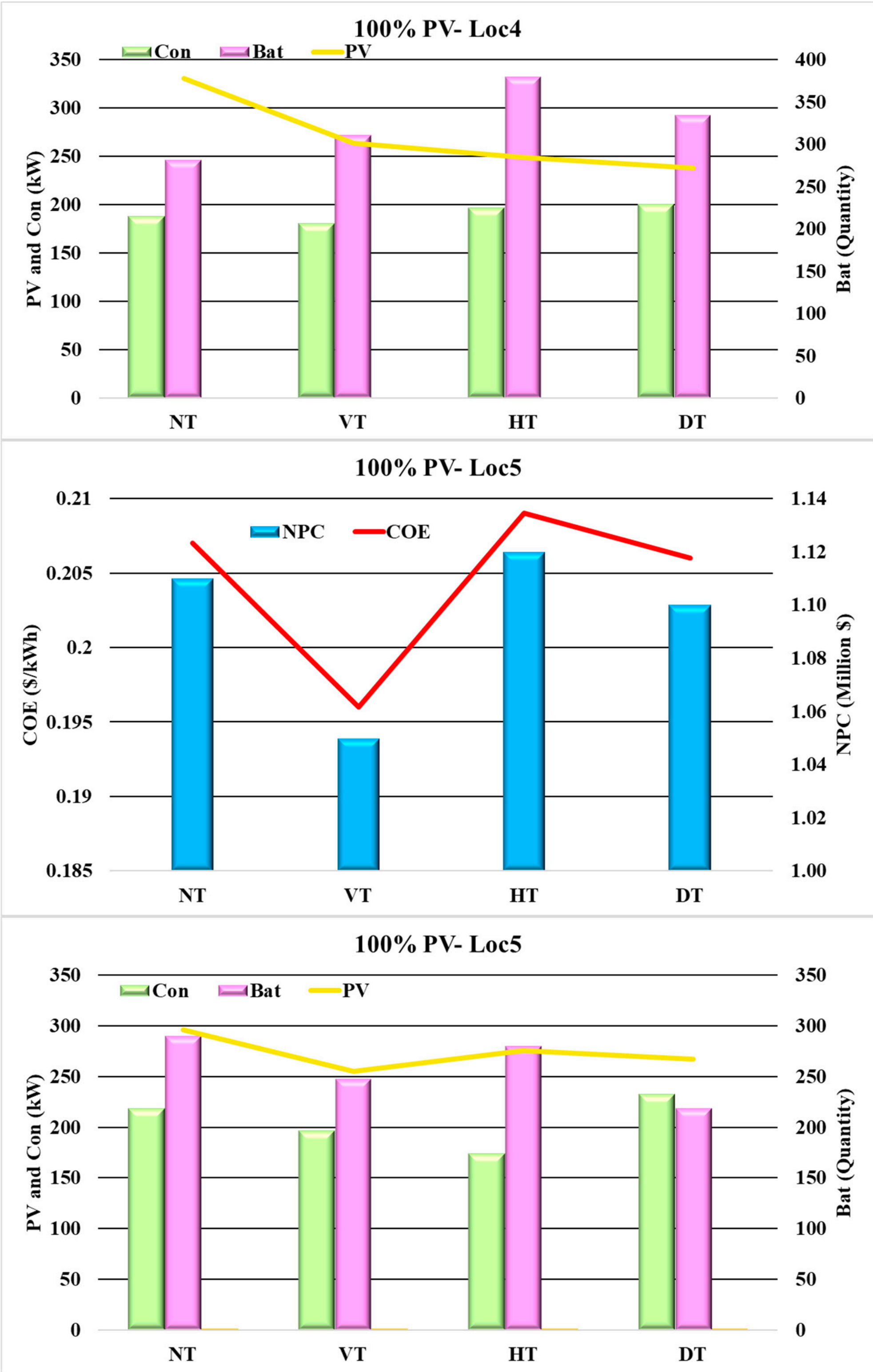

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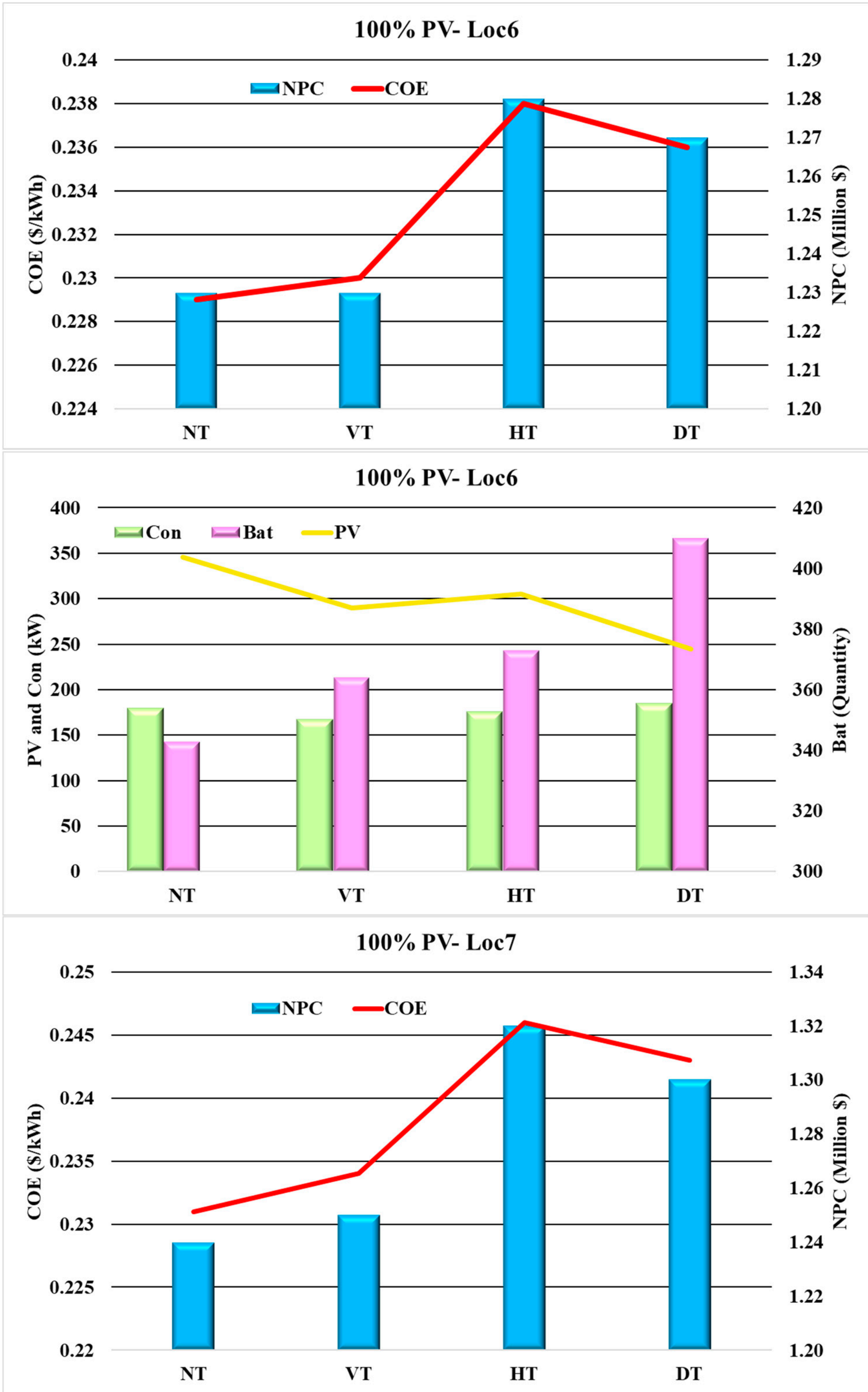

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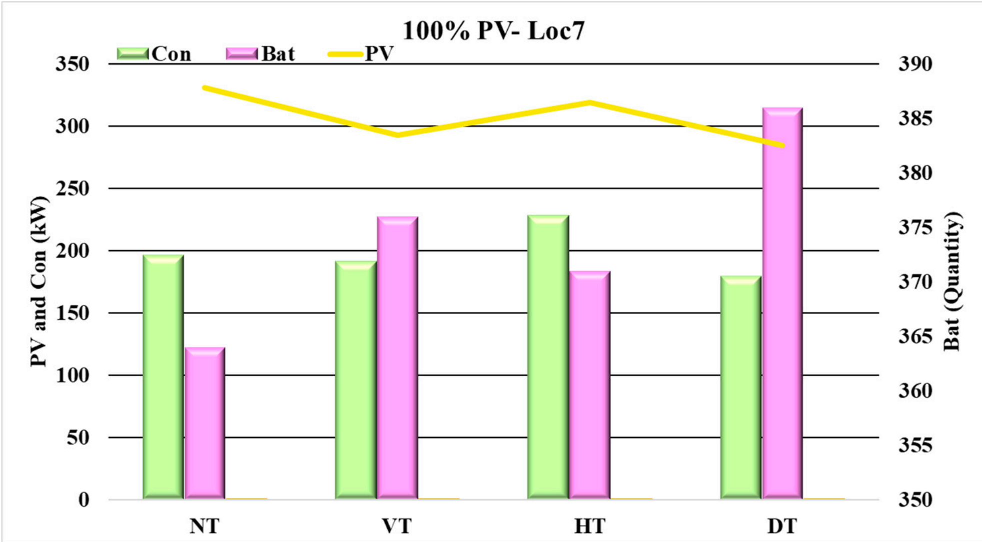

Figure 10. COE, NPC, and the size of the components under config 3.

To sum it up, Table 7, shows the best tracker systems under each configuration.

Table 7. The best tracker systems under config 1, config2, and config 3.

	Loc1	Loc2	Loc3	Loc4	Loc5	Loc6	Loc7
			The optimality of the trackers				
Config 1	DT	VT	VT	DT	DT	DT	VT
Config 2	DT	VT	VT	VT	DT	NT	VT
Config 3	VT	NT	NT	VT	VT	NT	NT

3.4. The Results of the Config 4

The results of config 4 show that in all locations, a 135 kW generator is needed. With a considered penalty of 16 USD/ton CO_2, the NPC and COE of this configuration are 1.47 million and 0.274 (USD/kWh), respectively. CO_2 production from generators is 397,642 kg/yr. The COE value of another study using this config without considering the CO_2 penalty is obtained at 0.105 (USD/kWh) [54].

3.5. The Results of the Sens 1

In Sens 1, where HRES uses 100 kW PV, the obtained COEs are calculated by multiplying the capital cost of PV by 0.7 to 1.4 of the values considered in Table 5. For example, $0.7 \times 1300 = 910$ (USD/kW) is considered for NT and with this new capital, the COEs of each location with NT are calculated. The average values are reported in Figure 11. Considering the obtained COEs, the best tracker systems are presented in Table 8 where the prices of NT, VT, HT, and DT are given.

Table 8. The economic tracker system under Sens 1 based on the reported costs [16,48,55,56].

NT (USD/kW)	VT (USD/kW)	HT (USD/kW)	DT (USD/kW)	Economic Optimality
1820	2240	2240	2520	NT > VT > HT = DT
1690	2080	2080	2340	NT > VT > DT > HT
1560	1920	1920	2160	VT = NT > DT > HT
1430	1760	1760	1980	VT = NT > DT > HT
1300	1600	1600	1800	VT > NT > VT > HT
1170	1440	1440	1620	VT > NT > VT > HT
1040	1280	1280	1440	VT > NT = VT > HT
910	1120	1120	1260	VT > DT > NT > HT

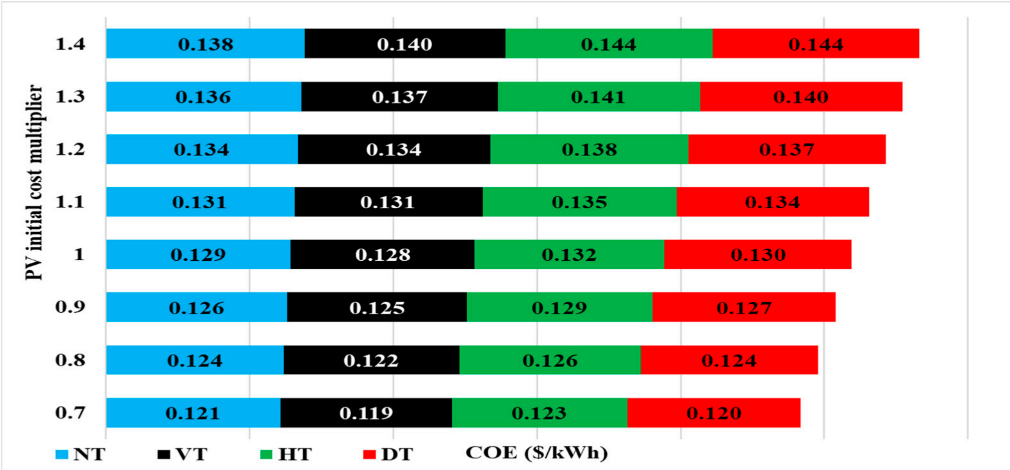

Figure 11. The obtained average of COE values under Sens 1.

3.6. The Results of the Sens 2

In Sens 2, where HRES uses 100 kW PV, the obtained COEs are calculated by considering different GHIs for each location and using different tracking systems. For example, by considering GHI = 4.5 (kWh/m^2/day) and using NT for all locations, the COEs are calculated, and the average values are reported in Figure 12. Based on the calculated COEs, the best trackers are presented in Table 9. For instance, where GHI is 6.5, the vertical tracker is a good choice.

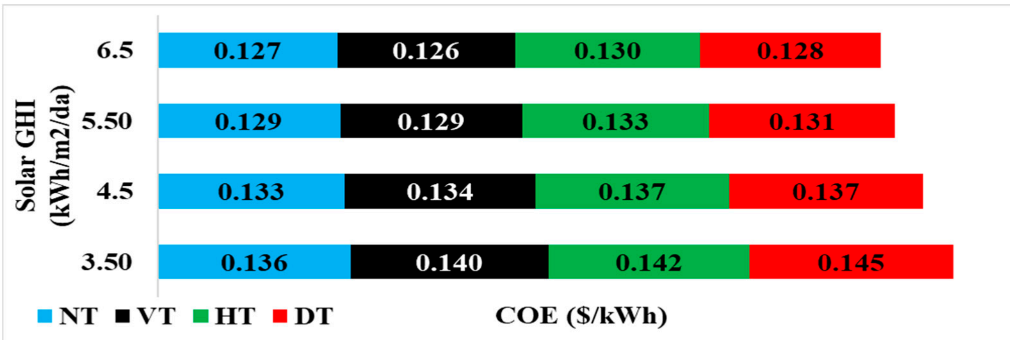

Figure 12. The obtained average of COE values under Sens 2.

Table 9. The economic tracker system under Sens 2.

GHI (kWh/m^2/day)	Economic Optimality
6.5	VT > NT > DT > HT
5.5	VT = NT > DT > HT
4.5	NT > VT > HT = DT
3.5	NT > VT > HT > DT

4. Conclusions

The aim of the current research is to investigate different tracking systems from economic and environmental aspects to find the best options for PV and tracking under the assumptions of the current study. In this regard, three kinds of tracker systems and a PV without a tracker, along with wind turbines, generators, and batteries are proposed for 7 locations in Saudi Arabia. The most important findings are as follows:

- With changes in location and the same configurations and economic parameters, the best economic tracker and environmentally friendly system in an HRES that can use free sizes of PV, WT, Gen, and Bat would differ.

- Considering the same tracker for different locations in an HRES that can use free sizes of PV, WT, Gen, and Bat, the optimal size of PV panels would differ, resulting in changes in RFs and CO_2 emissions.
- If the social cost (penalty) of CO_2 emission is considered, with changes in location (where renewable sources would also differ), COEs would differ under various tracking systems such that the higher the RF, the lower the COE.
- The most efficient tracker would be the dual-axis tracking system since it can increase power production by 35% more than PV without a tracker. Additionally, the vertical tracker and horizontal continuous adjustment tracker would increase the power production of the PV by 22% and 8%, respectively.
- In the case of changing the price of PV panels for NT, VT, HT, and DT from 0.7 to 1.2 of the proposed initial capital costs (NT: 1300, VT:1600, HT:1600, and DT: 1800 USD/kW), a vertical tracker would be the best choice and for higher prices up to 1.4 of the initial costs, NT would be more economic.
- For solar GHIs between 5.5 to 6.5 kWh/m^2/day, a vertical tracker is more economical while for lower GHIs using a tracker would not be economical.

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Nomenclature

Bat	Battery
COE	Cost of energy
Con	Converter
CI	Clearness index
Config	Configuration
da	Day
DT	Dual axis tracker
Ee	Excess electricity
Gen	Generator
GHI	Global horizontal irradiation
HT	Horizontal tracker
HOMER	Hybrid optimization model for multiple energy resources
HERES	Hybrid renewable energy system
h	Hour
Lat	Latitude
LCOE	Levelized cost of energy
Loc	Location
Long	Longitude
PV	Photovoltaic
NPC	Net present cost
NT	No tracking

Op	Optimum
O&M	Operation and maintenance
Qnt	Quantity
RF	Renewable fraction
Sens	Sensitivity analysis
Temp	Temperature
VT	Vertical tracker
WT	Wind turbine
yr	Year

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