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Comparative Numerical Energy and Performance Analysis of Solar Photovoltaic and Solar Thermal Power Generation

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ABSTRACT

This study analyses fixed and tracking solar photovoltaics and, solar thermal power. Performance in different locations was analysed for each configuration and technology using simulations based on a Typical Meteorological Year data. The study analysed a 25MWp solar photovoltaic and solar thermal power plants in each of the eleven selected locations in Zimbabwe. The performance of the solar photovoltaic and solar thermal power plants under different meteorological variables were assessed for all the selected locations. It was shown that different configurations together with different technologies have different conversion efficiencies. A high solar thermal conversion efficiency was found to be 18.718% in Gweru while it was 15.502% for solar photovoltaics in Mutare. The study also showed that highest insolation and clearness index values were found in Gweru. The average energy generated by the fixed photovoltaic collectors, tracking photovoltaic collectors and the Concentrating Solar Power plant were respectively 47.38GWh, 68.18GWh and 192.86GWh. There was a maximum percentage difference in the LCoE generated of 32.03% between the fixed PV collectors and the Concentrating Solar Power plant and a difference of 4.74% was realised between the tracking photovoltaics and Concentration Solar Power.

1. Introduction

Globally, there is a huge drive towards the use of clean and alternative energy sources to avoid and mitigate the negative impacts of fossil fuel based energy sources. The use of these alternative energy sources has a significant contribution to mitigate the environmental concerns associated with fossil fuel based energy systems and aid in the reduction of Greenhouse Gases (GHGs) [1-3]. Fossil fuels are known for their negative impacts to the environment including global warming that the world is currently seized with [4,5]. Solar energy is one of the clean and renewable sources of alternative energy available in abundance which is theoretically capable of meeting the global energy demands and is envisaged to meet the future energy needs [6-9].

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This energy source can be harvested in different forms with major classifications being solar thermal and solar photovoltaics (PVs) [10]. Solar thermal collectors are employed to convert solar irradiance into heat while solar PV collectors convert solar irradiance into electrical energy [7,11].

Historically, solar thermal collectors are more efficient when compared to PV collectors and some classes of solar thermal collectors such as the Flat Plate collector have a low running cost [12]. The efficiency of PV collectors ranges from 5% - 20% while that of thermal collectors range from 35% - 60% [13]. The efficiency of PV collectors is severely affected by temperature increase and as much as 0.45% of the energy is lost due to temperature [14,15]. Although PV collectors are less efficient, their price has been significantly reduced and in the last decade there has been a reported improvement of the PV efficiency up to 23% [16-18].

Clean and affordable energy is an integral requirement in modern day life and this should be obtained preferably from a clean energy source such as solar energy and this should be harvested in as efficient way as possible [19,20]. The generation of electricity using solar energy can be achieved through the use of solar PVs or concentrating solar thermal collectors or a combination of PV and thermal collectors [21]. While solar thermal collectors can be attached with Thermal Energy Storage Systems, PV collectors require battery energy storage systems [16]. Concentrating Solar Power (CSP) systems converts the Direct Normal Irradiance (DNI) only into useful energy while solar PV systems can convert both DNI and Diffuse energy [22].

The parabolic trough collector has a similar overall efficiency (defined by Eq. (1)) to that of solar PV collectors of around 12% where η is the total system efficiency, E_t is the total electrical energy generated and G_t is the total incident irradiance [23].

$$\eta = \frac{E_t}{G_t} \tag{1}$$

A study by Reddy *et al.,* [24] revealed that Parabolic Trough Collectors (PTC) have their thermal efficiency significantly affected by optical errors in areas with low irradiance and high declination. A study of a PTC power plant in Morocco revealed the importance of the Direct Normal Irradiance (DNI) as the determining factor of the annual energy generated by a PTC Concentrating Solar Power (CSP) plant [25]. In a study by Ahlgren *et al.,* [26], it was also noted that the DNI is a good estimator of PTC performance. A study by Mansour *et al.,* [27] also noted that the performance of a PTC is highly dependent on the incoming irradiance angle of incidence and other collector parameters. Khakrah *et al.,* [28] investigated the impact of wind speed on a PTC power plant and found that the thermal efficiency significantly reduced by 7% at a wind velocity of 10 m/s when compared to still air. Wang *et al.,* [29] investigated a PTC in China and found that the optical efficiency can reach up to 70%.

Desideri and Campana [22] analysed and performed a comparative analysis in a solar PV power plant and a solar thermal power plant designed for the same peak power production and for the same collector area. The study revealed that the solar thermal power plant produced electric energy at a lower Levelised Cost of Energy (LCoE) due to the availability of energy storage.

Dhivagar *et al.,* [30] assessed the economic, exergy and energy impact of magnetic powder as a thermal storage and porous media in a modified solar still. The results revealed a higher evaporative and convective heat transfer rates of respectively 39.8% and 14.5% respectively.

The present study outlines the importance of making a proper choice in the selection of a relevant solar power generation technology that suits the location of installation. The predicted plan to have 8000GW of solar installed capacity by 2050 requires that installation site be critically analysed to determine the best locations for solar PV or thermal power plants [31]. Due to variability of the operating characteristics of solar thermal and PV, an analysis of their location dependency is performed in this study. While the CSP power systems can only convert the DNI component of solar radiation, solar PV can convert both the DNI and Diffuse components. This makes it more complex to decide on the technology to be used in a particular location especially locations characterised by stochastic sunshine and cloud cover conditions. A proper analysis is thus required using historical data to determine the best technology that can be deployed under such conditions. This study therefore explores and analyses the performance of each solar technology in the selected locations to determine the best option i.e. fixed solar photovoltaic, tracking solar photovoltaic or solar thermal. The conversion efficiencies and the annual energy generated was determined for each solar technology with respect to the location. Comparisons were made in terms of the NPV and the LCoE for each location.

2. Methodology

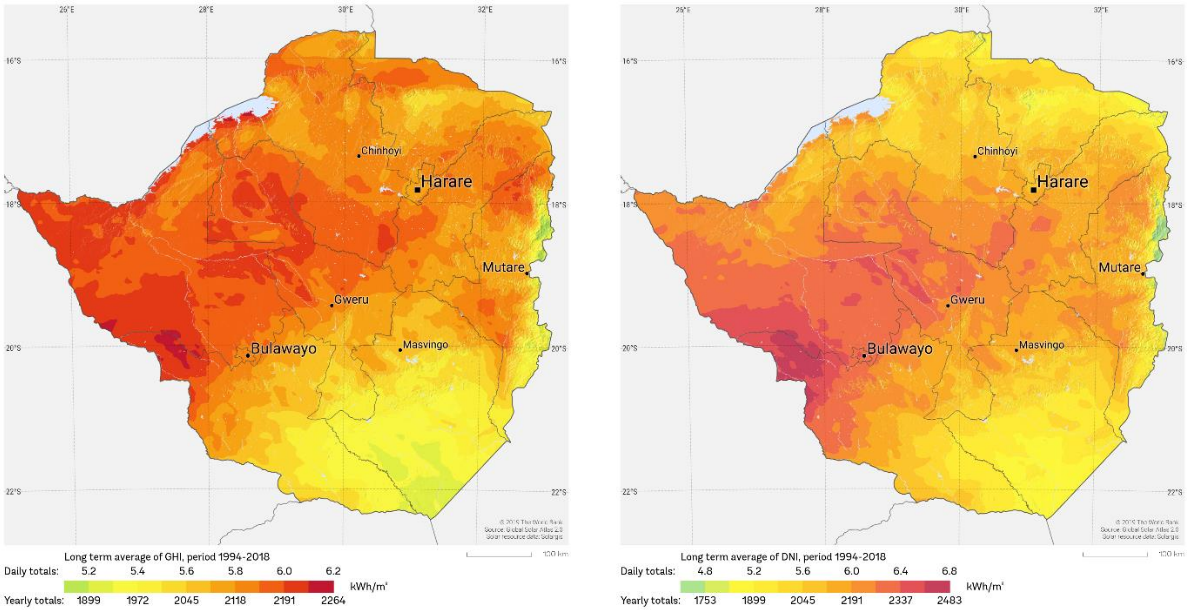
2.1 Location and Data Gathering

Different locations were selected for study in Zimbabwe and these include Nyanga, Harare, Beitbridge, Lupane, Kariba, Marondera, Gwanda, Bindura and Gweru. A complete list of the locations studied is shown in Table 1. The solar resource maps for the different locations are given in Figure 1. These locations were selected to have a full coverage of the whole country in the analysis. Nyanga and Mutare are located in the Eastern part of the country while, Harare and Marondera are located to the west of Nyanga. Bindura, Chinhoyi and Kariba are located in the Northern half of the country. Beitbridge, Gwanda and Chiredzi are to the South. Gweru is in the central part while Lupane is located in the Western part of Zimbabwe. These locations were selected based on the variability of meteorological conditions and hence the expected insolation in these areas is also varying. These locations have varying amounts of DNI as well as GHI thus the solar power generation technologies that would give the maximum energy generation are expected to be dependent on the insolation received based on metrics such as annual energy generated (E_a), Net Present Value (NPV) and Levelised Cost of Energy (LCoE).

Table 1
Location characteristics

	Location	Latitude	Longitude	Elevation
1	Beitbridge	22.2018° S	29.9915° E	468m
2	Bindura	17.3041° S	31.3274° E	1118m
3	Chinhoyi	17.3622° S	30.1987° E	1187m
4	Gwanda	20.9429° S	29.0071° E	974m
5	Gweru	19.4657° S	29.8124° E	1425m
6	Harare	17.8216° S	31.0492° E	1481m
7	Kariba	16.9557° S	27.9718° E	619m
8	Lupane	18.9300° S	27.7593° E	980m
9	Marondera	18.1885° S,	31.5487° E	1689m
10	Mutare	18.9758° S	32.6691° E	1095m
11	Nyanga	18.2201°S	32.7464°E	1738m

The meteorological data for a Typical Meteorological Year (TMY) were obtained from the National Solar Radiation Database (NSRDB (nrel.gov)). The necessary data for the computation and simulation of energy generated by both the PV and thermal power plants were collected and this included DNI, GHI and Temperature.



(a) (b)

Fig. 1. Solar resource maps in Zimbabwe for (a) GHI and (b) DNI [32]

2.2 Solar PV and Thermal Power Plants Design and Simulation

The solar power plants were designed to produce the same peak power for both the PV and thermal power plant. PV and thermal power plants with a peak capacity of $25MW_{ac}$ were designed for simulation purposes. The PV power plants were designed with no storage and were assumed to be connected to the national grid while the CSP power plant had a thermal storage capacity of 150 hours. A comparative analysis was carried out on these two power plants with similar peak power. The solar PV system had a peak installation capacity of $32.5MW_{dc}$ with a DC to AC ratio of 1.3. The solar thermal system had a gross design of $27.8MW_e$ with a conversion factor of 0.9 with a solar multiple of 6. Both the design for PV and CSP were targeting a $25MW_e$ net output under optimum conditions. The total module area for solar PV was 171,052,631.579m^2 while the total aperture reflective area was 863,280m^2 for solar thermal.

2.2.1 PV power plant design and analysis

PV collectors were assumed to be installed at fixed optimum tilt angles depending on the particular location while an azimuth of 180^o was used for all locations. The optimum tilt angles used were; 22.2^o for Beitbridge, 17.3^o for Bindura, 17.4^o for Chinhoyi, 20.9^o for Gwanda, 19.5^o for Gweru, 17.8^o for Harare, 17.0^o for Kariba, 18.9^o for Lupane, 18.2^o for Marondera, 19.0^o for Mutare and 18.2^o for Nyanga.

A similar $25MW_e$ PV power plant with single axis tracking was also considered in this study for each location. Energy simulations were performed using System Advisor Model (SAM) for the solar PV power plants analysed in this study. This study realised that the amount of energy generated is dependent on the geographical location and installation parameters i.e. tilt (β) and azimuth (γ) angles. The tilt angle signifies the inclination of the PV collector relative to the horizontal while the azimuth angle signifies the angular deviation relative to the geographic South. In this study, an azimuth of 180^o is equivalent to 0^{o}N.

The solar PV arrays were stacked one array behind the other and the minimum distance (d_p) between the solar PV arrays was determined using Eq. (2) where $h_o = W_p Sin\beta$, ϕ is the latitude of location, W_p is the width of the solar PV array and β is either the optimum tilt angle or maximum tilt angle respectively for fixed PV arrays and tracking PV arrays [33].

The sun position was computed using the algorithm proposed by Michalsky [34] while the geometrical calculations for the angle of incidence for the fixed solar PV plants was computed using Eq. (3) where tilt is Φ, solar azimuth is γ_s, surface azimuth is γ, and solar zenith angle is θ_z. An algorithm by Marion and Dobos [35] was adopted for the single axis tracking as shown by Eq. (4) where R should give the minimum angle of incidence and γ_a is the azimuth of the tracker axis.

$$d_p = \frac{(0.707 h_o)}{\tan[\sin^{-1}(0.648\cos\Phi - 0.399\sin\Phi)]} \tag{2}$$

$$\alpha_{fixed} = \cos^{-1}[\sin(\theta_z)\cos(\gamma - \gamma_s)\sin(\Phi) + \cos(\Phi_s)\cos(\Phi)] \tag{3}$$

$$R = \tan^{-1}\left\{\frac{\sin\theta_z \sin(\gamma_s - \gamma_a)}{\sin\theta_z \cos(\gamma_s - \gamma_a)\sin\beta_a + \cos\theta_z \cos\beta_a}\right\} + \omega \tag{4}$$

where,

$\omega = 0°$ if X= 0, or if X> 0 and $(\gamma_s - \gamma_a) > 0$, or if X< 0 and $(\gamma_s - \gamma_a) < 0$

$\omega = +180°$ if X< 0 and $(\gamma_s - \gamma_a) > 0$

$\omega = -180°$, if X> 0 and $(\gamma_s - \gamma_a) < 0$

The hourly electrical energy generated by the PV power plants in the different locations in this study was computed using Eq. (5) where the daily energy generated is made up of the summation of the hourly energy generated from sunrise (R_s) to sunset (S_s) as shown by Eq. (6). Where P_a is the DC power rating of the PV array with T_{cell} being the operating cell temperature and the transmitted plane of array irradiance is I_{tr}. The reference cell temperature T_{ref} is taken as 25°C, and reference irradiance (G) is 1000 W/m^2 while the temperature coefficient is γ. The annual energy generated ($E_{pv,annual}$) is computed by summing up the individual daily energy generated for the whole year from day 1 up to day 365 as shown by Eq. (7). A standard crystalline Silicon solar panel was considered in this study and its specifications were 19% efficiency with Anti-reflective glass, Temperature Coefficient of Power being -0.37 %/°C while the fill factor was 77.8%. Total system losses of 14% were considered in the simulation.

$$E_h = \frac{I_T}{G_r} P_a \left[1 + \left(T_{cell} - T_{ref}\right)\right] \tag{5}$$

$$E_d = \sum_{R_s}^{S_s} \frac{I_T}{G_r} P_a \left[1 + \left(T_{cell} - T_{ref}\right)\right] \tag{6}$$

$$E_{pv,annual} = \sum_{d=1}^{365} E_d \tag{7}$$

2.2.2 Solar thermal plant design and analysis

A 25MW$_p$ power plant was designed for use in this study. The design of the power plant took into consideration the available solar energy, thermal losses and electrical efficiency of the thermal power plant. The hourly thermal energy generated by the thermal power plant was determined using a relationship shown by Eq. (8) adopted from Duffie and Beckman [36].

$$Q_{th} = \eta_o K_b(\theta) I_b - a_1(T_m - T_a) - a_2(T_m - T_a)^2 - a_3(T_m - T_a)^3 \quad (8)$$

$$K_b(\theta) = 1 - b_o\left(\frac{1}{\cos\theta} - 1\right) \quad (9)$$

$$\cos\theta = \left(\cos^2\theta_z + \cos^2\delta\sin^2\omega\right)^{\frac{1}{2}} \quad (10)$$

η_o is the optical efficiency of the parabolic trough thermal collectors for the DNI, $K_b(\theta)$ is the incidence angle modifier, and is given by Eq. (9) with b_o being the coefficient for the incidence angle modifier. I_b is the Direct Normal Irradiance while a_1 is a constant part of the overall heat loss coefficient of the receiver, a_2 is the temperature dependent part of the overall heat loss coefficient of the receiver while a_3 is the pipeline heat loss coefficient. T_a and T_m are respectively the ambient temperature and the Heat Transfer Fluid (HTF) temperature.

In this study, the parabolic troughs used mimicked those used in a study by Desideri and Campana [22] and the values for η_o, a_1, a_2, a_3 and b_o were respectively 0.80, 0.40, 0.00, 0.05 and 0.10. The parabolic trough thermal collectors were configured in the North-South orientation as this orientation was reported to have more annual energy yield compared to the East-West orientation [22]. Consequently, the angle of incidence was given by Eq. (10) where θ_z is the zenith angle with declination being δ, and the hour angle given by ω. Eq. (11) gives the slope of the collector surface where the surface azimuth is given by γ while the solar azimuth angle is given by γ_s [36]. Energy simulations were performed using SAM for the solar thermal power plant.

The shading between adjacent collectors was minimised using Eq. (12) where η_s is the shading efficiency, d is the distance between adjacent collector rows while A_{ap} is the collector aperture area. The efficiencies with regards to the power block (η_{pb}), and the turbine alternator (η_{ta}) were respectively taken as 0.38 and 0.95 [37]. The annual electrical energy generated by the thermal power plant was computed using Eq. (13).

$$\tan\beta = \tan\theta_z \left|\cos(\gamma - \gamma_s)\right| \quad (11)$$

$$\eta_s = \frac{d}{A_{ap}}\cos\beta \quad (12)$$

2.3 Comparative Analysis

The two solar generation technologies were evaluated against each other using metrics including the annual energy generated (E_a) and the Overall efficiency (η_{ov}) given by Eq. (13) where E_e is the total electricity generated annually while G_T is the total insolation received annually [22].

$$\eta_{ov} = \frac{E_e}{G_T} \tag{13}$$

$$NPV = \sum_{t=1}^{n} \frac{C_t}{\left(1+r\right)^t} - I_0 \tag{14}$$

$$LCoE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{\left(1+r\right)^i}}{\sum_{t=1}^{n} \frac{E_t}{\left(1+r\right)^t}} \tag{15}$$

$$E_t = E_o\left(1 - \frac{D_R}{100}\right)^t \tag{16}$$

Comparisons were also made in terms of the Net Present Value (NPV) and Levelised Cost of Energy (LCoE) for each of fixed solar PV, tracking solar PV and solar thermal generation plants. The NPV was assessed as in Eq. (14) where n, C_t, I_o and r are respectively the year, net annual cash flows in year t, initial investment and the discount rate. The LCoE was computed using Eq. (15) where, M_t is the O&M expenditure in year t; E_o is the electricity produced in the first operational year; E_t = electricity generated in year t; n is the expected power plant lifetime; D_R is the degradation factor and, in this study, it is assumed to have an annual output drop of 0.5% [38]. The NPV is the net value of expected inflows against cash outflows while LCoE analysis performs the life cycle cost assessment considering lifetime costs divided by energy production. The fixed initial costs and the O&M costs for each technology are shown in Table 2. An interest rate of 12% was used for a project lifetime of 25 years with a feed-in-tariff of US$0.10. Comparisons were also made using results in literature to ascertain the validity of the NPV and LCoE for the different technologies studied [39-41].

Table 2
Economic variables

	PV_f	PV_t	CSP
Initial Cost	$33,800,000.00	$39,000,000.00	$144,615,600.00
O&M	$422,500.00	$487,500.00	$1,651,320.00
P/Ain	7.8431	7.8431	7.8431
FiT	US$0.10	US$0.10	US$0.10

3. Results and Discussions

3.1 Analysis of Meteorological Variables

The averaged values of meteorological parameters for the different locations used in the simulations are shown in Table 3. The values of the average daily insolation for each location are also shown in Figure 2.

Table 3
Averaged values of important parameters in solar energy simulations

	Location	G_{avg}	K_t	T	W_s	R_{avg}	W_d
1	Beitbridge	5.18	0.56	23.17	4.29	28.17	3.57
2	Bindura	5.48	0.58	23.11	4.51	71.08	6.43
3	Chinhoyi	5.52	0.58	22.97	4.43	65.75	6.80
4	Gwanda	5.33	0.58	21.34	4.10	38.83	5.24
5	Gweru	5.60	0.60	20.25	4.36	56.50	6.08
6	Harare	5.46	0.58	20.62	4.51	73.92	7.24
8	Kariba	5.51	0.59	24.78	4.65	34.83	5.58
9	Lupane	5.53	0.58	25.68	4.75	31.61	4.81
10	Marondera	5.56	0.59	21.32	4.60	68.67	6.31
11	Mutare	5.09	0.54	22.87	4.66	96.58	7.93
12	Nyanga	5.16	0.55	23.10	4.70	90.17	9.49

Where G_{avg} (kWh/m²/day) is the average daily insolation, K_t is the average daily clearness index, T(°C) is the average daily temperature, W_s(m/s) is the average wind speed, R_{avg}(mm) is the average monthly precipitation, W_d is the average number of wet days in a month.

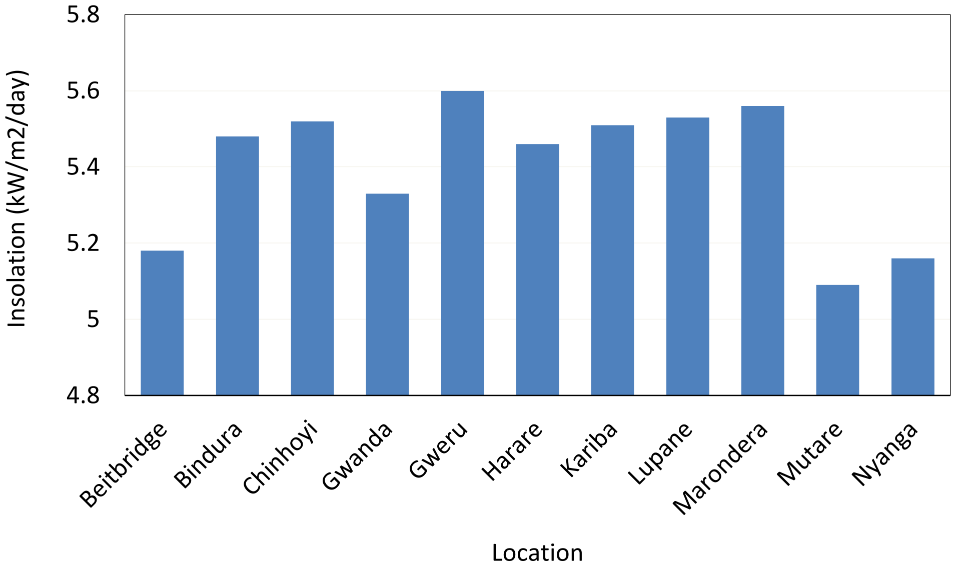


Fig. 2. Average daily insolation for each location

An analysis of these parameters revealed a maximum daily averaged insolation of 5.60 kWh/m²/day experienced in Gweru which also had the highest clearness index value of 0.6. On the other hand, the least values of insolation and clearness index were found in Mutare. Generally, an average daily insolation of 5.40 kWh/m²/day was measured for all locations with a corresponding average clearness index of 0.58. The average daily temperature and wind speed and, average monthly precipitation was found to be 22.66°C, 4.51m/s and 59.65mm respectively. The study revealed that locations with high values of insolation also had a corresponding high clearness index.

A further comparison of the daily averaged insolation for 3 locations was done in this study for a location with a low average daily insolation (Nyanga), a location with an intermediate value of daily averaged insolation (Gwanda) and the location with the highest averaged daily insolation (Gweru) as show in Figure 3. The comparison revealed that the insolation values in Nyanga were always less than insolation values elsewhere. However, although Gweru had the highest insolation, the study revealed that from the month of November to February, the insolation values in Gweru are often lower than those in Gwanda. This phenomenon could be attributed to the fact that this period is the rainy season and more rainfall is experienced in Gweru compared to Gwanda and thus insolation is significantly reduced. The study revealed that the areas known to be associated with arid conditions do not necessarily have high insolation compared to the non-arid regions. For example, Gweru, Marondera and Chinhoyi are not classified as arid but they have the highest insolation compared to Beitbridge, Gwanda and Kariba which are arid regions. This could partly be attributed to the fact that these arid areas are also characterised by lower clearness index values. For example, Gweru has a clearness index of 0.60 while Beitbridge has a clearness index of 0.56. The wet eastern highlands regions of Nyanga and Mutare are both associated with low insolation and clearness index values partly due to the persistent cloudy weather.

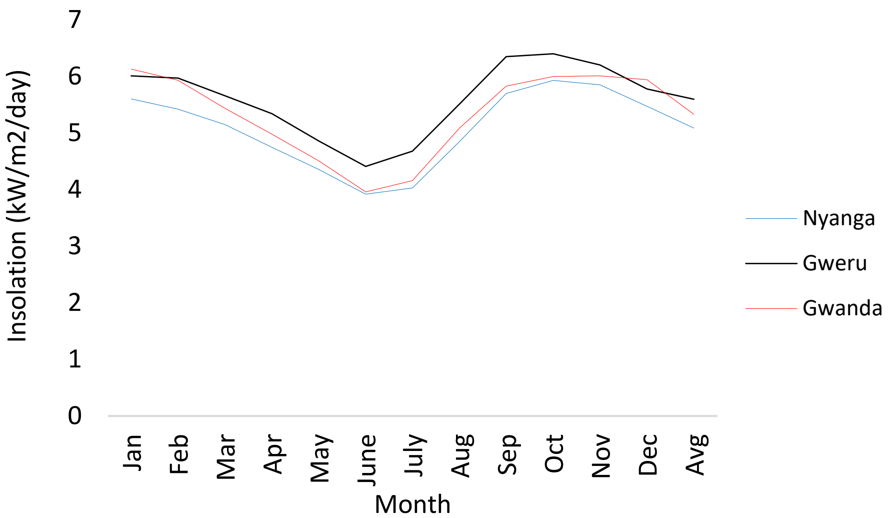


Fig. 3. Comparison of insolation from three different locations

3.2 Solar Energy Generated

The energy generated by the different PV configurations i.e. fixed PV collectors (PV_f) and tracking PV collectors (PV_t) and, the CSP power plant is shown in Table 4. Gweru, Marondera and Bindura had the highest CSP generation of all the locations studied and this is attributed to the fact that these are also the areas with the highest clearness index values thus providing a higher DNI component necessary for CSP applications. From Figure 4, Kariba and Beitbridge had the lowest CSP power generation. With regards to tracking solar PV, Gweru, Lupane and Marondera had the highest power generation while for non-tracking solar PV Harare, Bindura and Marondera had the highest power generation. The least power generation from fixed solar PV is from Beitbridge and Gwanda while Beitbridge and Kariba had the least power generation from tracking solar PV. The low power generation from solar PV in these regions is partly attributed to the high temperatures experienced in these areas which have an effect of reducing the solar power generated. The average power generated was 47.38, 68.18 and 192.86 respectively for fixed solar PV, tracking solar PV and CSP.

Table 4
Annual energy generated for the locations studied

		Annual Energy (GWh)		
	Location	PV_f	PV_t	CSP
1	Beitbridge	43.12	65.97	179.97
2	Bindura	48.98	68.84	196.21
3	Chinhoyi	47.90	67.38	191.84
4	Gwanda	44.87	68.23	192.13
5	Gweru	47.51	69.52	198.44
6	Harare	48.75	68.60	193.38
7	Kariba	47.69	66.37	189.59
8	Lupane	47.35	68.96	194.99
9	Marondera	49.28	69.75	198.10
10	Mutare	47.01	67.07	193.40
11	Nyanga	47.68	67.32	193.41

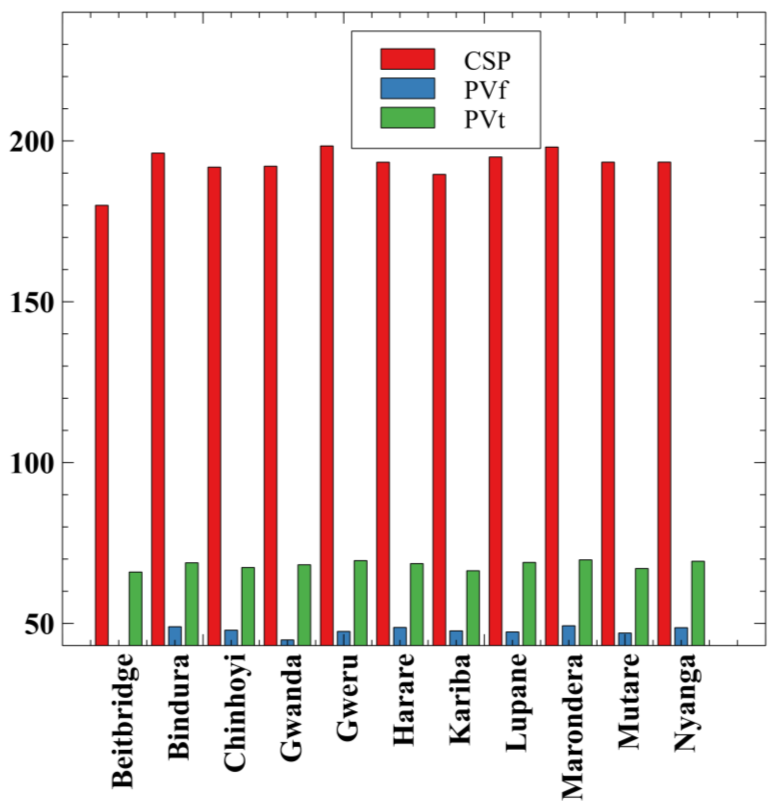


Fig. 4. Energy generated from different locations

There was an average percentage difference of 75.44% between power generated by CSP and fixed solar PV while it was 64.64% between CSP and tracking PV. The difference in energy generated by fixed PV and tracking PV was 30.52%. The main reason for a large percentage difference between CSP and PV is attributed to the 150h solar thermal storage incorporated in the CSP power plant. This had an effect of prolonging power generation even in times of non-availability of solar energy. The study revealed that the hot and arid areas do not necessarily provide the best locations for solar power generation in terms of the energy generated. This is because of the other factors which affect power generation and these include the clearness index which in a way is a measure of the “quality” of the insolation reaching the solar collectors or solar panels. On the other hand, temperature is a very critical variable that negatively affects power generation in solar PV power plants. In such circumstances, relatively cool areas with high insolation and clearness index tend to be characterised with higher solar power generation for both PV and CSP. The higher CSP generation achieved would imply that CSP has a good potential in Zimbabwe than fixed PV installations.

3.3 Conversion Efficiency and Capacity Factor

The different locations exhibited different conversion efficiencies for the different configurations. Average conversion efficiencies of 13.5%, 14.86% and 17.86% were respectively realised for PV_f, PV_t and CSP. It was found that CSP has higher conversion efficiencies compared to PV technology. A maximum conversion efficiency of 18.718% was recorded for CSP in Gweru while a maximum conversion efficiency of 15.502% was recorded for PV_t in Mutare. The different ambient conditions in each location accounted for the differences in the conversion efficiencies (see Table 5). The results revealed that conversion efficiencies were especially higher for both PV and CSP in clear sky locations while they were even higher for PV in cooler locations with clear sky conditions. This can be attributed to the fact that PV conversion is more efficient at lower temperatures than at higher temperatures. On the other hand, hotter locations offer a lower temperature gradient between the receiver and the ambient and hence a lower efficiency drop is experienced unlike when there is a higher temperature gradient.

Table 5
Comparison of conversion efficiency

	Conversion efficiency (%)		
Location	η_{ov} (PV_f)	η_{ov} (PV_t)	η_{ov} (CSP)
Beitbridge	12.807	14.983	17.372
Bindura	13.751	14.779	17.902
Chinhoyi	13.350	14.361	17.377
Gwanda	12.951	15.060	17.023
Gweru	13.052	14.605	18.718
Harare	13.736	14.781	17.709
Kariba	13.316	14.171	17.204
Lupane	13.173	14.671	18.630
Marondera	13.636	14.759	17.815
Mutare	14.209	15.502	16.998
Nyanga	14.114	15.305	16.741

The highest capacity factors for PV_f and PV_t were reported for Marondera while for CSP it was Gweru as shown in Table 6. This is attributed to the fact that there is more utilisation of solar thermal energy in Gweru than in Marondera which is relatively cooler and most suitable for solar PV. The study revealed that the capacity factor is always higher for CSP compared to both PV_f and PV_t for all locations. This is attributed to the thermal storage capacity incorporated to the CSP plants analysed in the study. This would allow additional power generation in the absence of solar insolation and hence prolong the power generation period.

Table 6
Capacity factor

		Capacity factor (%)		
	Location	PV_f	PV_t	CSP
1	Beitbridge	15.1	23.2	82.1
2	Bindura	17.2	24.2	89.5
3	Chinhoyi	16.8	23.7	87.5
4	Gwanda	15.8	24.0	87.7
5	Gweru	16.7	24.4	90.5
6	Harare	17.1	24.1	88.2
7	Kariba	16.8	23.3	86.5
8	Lupane	16.6	24.2	89.0
9	Marondera	17.3	24.5	90.4
10	Mutare	16.5	23.6	88.3
11	Nyanga	17.1	24.3	88.2

3.4 Economic Analysis

The study revealed average LCoE values of 6.72c, 5.25c and 5.35c respectively for PV_f, PV_t and CSP. The LCoE of 6.27c is comparable to the result by Zainali *et al.,* [42] who reported an average LCoE of 1.02SEK in Sweden while Abdelhady [43] reported a LCoE of 13.38c for a Stirling Dish collector. The PV_t showed the lowest LCoE making it the overall most desirable technology. The fixed PV generation plants had the highest LCoE and thus making them the least desirable. Marondera had the least LCoE for both PV_f and PV_t while Gweru had the least LCoE for CSP. Such location based variations were also reported in a study by Desideri and Campana [22]. There was an average percentage difference of 2% in the LCoE between PV_t and CSP. This indicates an almost equal potential in harnessing solar energy as either PV_t or CSP. However, in all circumstances, the study favoured PV_t instead of CSP as shown in Table 7. Analysis of the NPV indicates that PV_f is not desirable at all in Beitbridge, Gwanda and Mutare while it can also be concluded that it is not a good option in Lupane, Gweru and Kariba.

Table 7
LCoE and NPV

		LCoE ($)			NPV (US$'Millions)		
	Location	PV_f	PV_t	CSP	PV_f	PV_t	CSP
1	Beitbridge	7.38	5.43	5.70	-3.29	14.63	104.04
2	Bindura	6.49	5.20	5.26	1.30	16.88	116.78
3	Chinhoyi	6.64	5.32	5.38	0.45	15.73	113.35
4	Gwanda	7.09	5.25	5.37	-1.92	16.40	113.58
5	Gweru	6.70	5.15	5.21	0.15	17.41	118.52
6	Harare	6.52	5.22	5.34	1.12	16.69	114.56
7	Kariba	6.67	5.40	5.43	0.29	14.94	111.58
8	Lupane	6.72	5.19	5.29	0.02	16.97	115.82
9	Marondera	6.45	5.13	5.22	1.54	17.59	118.26
10	Mutare	6.77	5.34	5.33	-0.24	15.49	114.57
11	Nyanga	6.53	5.17	5.33	1.07	17.25	114.58

4. Conclusions

This study analysed the location dependent operating characteristics of solar CSP and PV and their influence on energy generated in each of the selected locations. The study intended to propose the best solar power generating technology for each of the selected locations based on the energy generated.

An analysis of the meteorological variables revealed a maximum daily averaged insolation of 5.60 kWh/m²/day while the least values of insolation were found in Mutare. On the other hand, an average daily insolation of 5.40 kWh/m²/day was measured. For all the locations studied, an average daily temperature of 22.66°C was recorded while an average wind speed 4.51m/s was measured. The study showed that locations with high insolation values had a corresponding high clearness index.

An analysis of the energy generated by the three technologies used in the study i.e fixed PV, tracking PV and CSP revealed that the average energy generated was respectively 47.38GWh, 68.18GWh and 192.86GWh.

A comparison of fixed PV, tracking PV and CSP revealed conversion efficiencies of 13.5%, 14.86% and 17.86% respectively for PV_f, PV_t and CSP. It was found that CSP has higher conversion efficiencies compared to PV technologies. A maximum conversion efficiency of 18.718% was recorded for CSP in Gweru while a maximum conversion efficiency of 15.502% was recorded for PV_t in Mutare. The analysis of the energy generated using the three technologies indicate a higher potential for PV_t and CSP in Zimbabwe. However, all locations ultimately favoured the tracking PV configuration instead of CSP although the difference in LCoE was averaging 2%.

Gweru had the highest insolation values compared to other locations but these were not sustained throughout the whole year as witnessed by lower insolation values in the rainy season where locations such as Gwanda had more insolation. This phenomenon can have an important impact on the selection of an installation location considering seasonal energy demands.

Different conversion efficiencies were recorded for different locations due to variations in ambient conditions for each location. Cooler locations had higher conversion efficiencies for PV while relatively hotter locations with higher clearness index values had higher conversion efficiencies for CSP.

References

[1] Khadka, Nasib, Aayush Bista, Binamra Adhikari, Ashish Shrestha, Diwakar Bista, and Brijesh Adhikary. "Current practices of solar photovoltaic panel cleaning system and future prospects of machine learning implementation." *IEEE Access* 8 (2020): 135948-135962. https://doi.org/10.1109/ACCESS.2020.3011553

[2] Samsudin, Muhammad Syazwan Nizam, Md Mizanur Rahman, and Muhamad Azhari Wahid. "Sustainable power generation pathways in Malaysia: Development of long-range scenarios." *Journal of Advanced Research in Applied Mechanics* 24, no. 1 (2016): 22-38.

[3] Loni, Reyhaneh, Gholamhassan Najafi, Rizalman Mamat, Mohd Fairusham Ghazali, and Nor Azwadi Che Sidik. "Nusselt Number Prediction for Oil and Water in Solar Tubular Cavity Receivers." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 97, no. 2 (2022): 157-174. https://doi.org/10.37934/arfmts.97.2.157174

[4] Shoeibi, Shahin, Hadi Kargarsharifabad, Nader Rahbar, Gholamreza Khosravi, and Mohsen Sharifpur. "An integrated solar desalination with evacuated tube heat pipe solar collector and new wind ventilator external condenser." *Sustainable Energy Technologies and Assessments* 50 (2022): 101857. https://doi.org/10.1016/j.seta.2021.101857

[5] Shoeibi, Shahin, Nader Rahbar, Ahad Abedini Esfahlani, and Hadi Kargarsharifabad. "Energy matrices, economic and environmental analysis of thermoelectric solar desalination using cooling fan." *Journal of Thermal Analysis and Calorimetry* 147, no. 17 (2022): 9645-9660. https://doi.org/10.1007/s10973-022-11217-7

[6] Khan, M. Z. H., M. R. Al-Mamun, S. Sikdar, P. K. Halder, and Md Rafiul Hasan. "Design, fabrication, and efficiency study of a novel solar thermal water heating system: towards sustainable development." *International Journal of Photoenergy* 2016 (2016). https://doi.org/10.1155/2016/9698328

[7] Awan, Ahmed Bilal, Muhammad Zubair, R. P. Praveen, and Abdul Rauf Bhatti. "Design and comparative analysis of photovoltaic and parabolic trough based CSP plants." *Solar Energy* 183 (2019): 551-565. https://doi.org/10.1016/j.solener.2019.03.037

[8] Abdullah, Amira Lateef, Suhaimi Misha, Noreffendy Tamaldin, Mohd Afzanizam Mohd Rosli, and Fadhil Abdulameer Sachit. "Numerical analysis of solar hybrid photovoltaic thermal air collector simulation by ANSYS." *CFD Letters* 11, no. 2 (2019): 1-11.

[9] Rebhi, Redha, Younes Menni, Giulio Lorenzini, and Hijaz Ahmad. "Forced-convection heat transfer in solar collectors and heat exchangers: a review." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 26, no. 3 (2022): 1-15. https://doi.org/10.37934/araset.26.3.115
[10] Jahromi, Mohammad Saleh Barghi, Vali Kalantar, Hadi Samimi Akhijahani, and Hadi Kargarsharifabad. "Recent progress on solar cabinet dryers for agricultural products equipped with energy storage using phase change materials." *Journal of Energy Storage* 51 (2022): 104434. https://doi.org/10.1016/j.est.2022.104434
[11] Liang, Vernon Yeoh Sheng, Nur Irwany Ahmad, Diyya Hidayah Abd Rahman, Aimi Athirah, Hazwani Zaidi, Saidatul Shema Saad, Nazrul Azril Nazlan, Habibah Mokhtaruddin, and Baseemah Mat Jalaluddin. "Development of Solar Tracking Robot for Improving Solar Photovoltaic (PV) Module Efficiency." *Journal of Advanced Research in Applied Mechanics* 61, no. 1 (2019): 13-24.
[12] Alawi, Omer A., and Haslinda Mohamed Kamar. "Performance of Solar Thermal Collector Using Multi-Walled Carbon Nanotubes: Simulation Study." *Journal of Advanced Research in Micro and Nano Engineering* 2, no. 1 (2020): 12-21.
[13] Zhao, Jiaxin, Zhenpeng Li, and Tao Ma. "Performance analysis of a photovoltaic panel integrated with phase change material." *Energy Procedia* 158 (2019): 1093-1098. https://doi.org/10.1016/j.egypro.2019.01.264
[14] Ma, Tao, Hongxing Yang, Yinping Zhang, Lin Lu, and Xin Wang. "Using phase change materials in photovoltaic systems for thermal regulation and electrical efficiency improvement: A review and outlook." *Renewable and Sustainable Energy Reviews* 43 (2015): 1273-1284. https://doi.org/10.1016/j.rser.2014.12.003
[15] Du, Dengfeng, Jo Darkwa, and Georgios Kokogiannakis. "Thermal management systems for photovoltaics (PV) installations: a critical review." *Solar Energy* 97 (2013): 238-254. https://doi.org/10.1016/j.solener.2013.08.018
[16] Rahaman, Md Habibur, and M. Tariq Iqbal. "A Comparison of Solar Photovoltaic and Solar Thermal Collector for Residential Water Heating and Space Heating System." *European Journal of Engineering and Technology Research* 4, no. 12 (2019): 41-47. https://doi.org/10.24018/ejeng.2019.4.12.1640
[17] Abdullah, Ali H., Adel A. Ghoneim, and Ahmad Y. Al-Hasan. "Assesment of grid-connected photovoltaic systems in the Kuwaiti climate." *Renewable Energy* 26, no. 2 (2002): 189-199. https://doi.org/10.1016/S0960-1481(01)00115-X
[18] Matuska, Tomas, and Borivoj Sourek. "Performance analysis of photovoltaic water heating system." *International Journal of Photoenergy* 2017 (2017). https://doi.org/10.1155/2017/7540250
[19] Buzás, J., and R. Kicsiny. "Transfer functions of solar collectors for dynamical analysis and control design." *Renewable Energy* 68 (2014): 146-155. https://doi.org/10.1016/j.renene.2014.01.037
[20] Kostić, Ljiljana T., and Jelena S. Aleksić. "Review of research, development and application of photovoltaic/thermal water systems." *Open Physics* 18, no. 1 (2020): 1025-1047. https://doi.org/10.1515/phys-2020-0213
[21] Kulkarni, Rohan S., Dhananjay B. Talange, Anjali A. Dharme, and Nitant V. Mate. "Development and performance analysis of solar photovoltaic-thermal (PVT) systems." *Sādhanā* 45 (2020): 1-5. https://doi.org/10.1007/s12046-020-01450-x
[22] Desideri, Umberto, and Pietro Elia Campana. "Analysis and comparison between a concentrating solar and a photovoltaic power plant." *Applied Energy* 113 (2014): 422-433. https://doi.org/10.1016/j.apenergy.2013.07.046
[23] Hagos, Dejene Assefa. "Techno-Economic Assesment of Parabolic Trough Steam Generation for Hospital." *KTH Industrial Engineering and Management* (2011).
[24] Reddy, K. S., C. S. Ajay, and Bohra Nitin Kumar. "Sensitivity study of thermal performance characteristics based on optical parameters for direct steam generation in parabolic trough collectors." *Solar Energy* 169 (2018): 577-593. https://doi.org/10.1016/j.solener.2018.03.088
[25] Aqachmar, Zineb, Amine Allouhi, Abdelmajid Jamil, Belgacem Gagouch, and Tarik Kousksou. "Parabolic trough solar thermal power plant Noor I in Morocco." *Energy* 178 (2019): 572-584. https://doi.org/10.1016/j.energy.2019.04.160
[26] Ahlgren, Benjamin, Zhiyong Tian, Bengt Perers, Janne Dragsted, Emma Johansson, Kajsa Lundberg, Jonatan Mossegård, Joakim Byström, and Olle Olsson. "A simplified model for linear correlation between annual yield and DNI for parabolic trough collectors." *Energy Conversion and Management* 174 (2018): 295-308. https://doi.org/10.1016/j.enconman.2018.08.008
[27] Mansour, Kheireddine, Rafika Boudries, and Rabah Dizene. "Optical, 2D thermal modeling and exergy analysis applied for performance prediction of a solar PTC." *Solar Energy* 174 (2018): 1169-1184. https://doi.org/10.1016/j.solener.2018.09.040
[28] Khakrah, Hamidreza, Amir Shamloo, and Siamak Kazemzadeh Hannani. "Exergy analysis of parabolic trough solar collectors using Al2O3/synthetic oil nanofluid." *Solar Energy* 173 (2018): 1236-1247. https://doi.org/10.1016/j.solener.2018.08.064

[29] Wang, Ruilin, Jie Sun, Hui Hong, and Qibin Liu. "An on-site test method for thermal and optical performances of parabolic-trough loop for utility-scale concentrating solar power plant." *Solar Energy* 153 (2017): 142-152. https://doi.org/10.1016/j.solener.2017.05.053
[30] Dhivagar, Ramasamy, Shahin Shoeibi, Hadi Kargarsharifabad, Mohammad Hossein Ahmadi, and Mohsen Sharifpur. "Performance enhancement of a solar still using magnetic powder as an energy storage medium-exergy and environmental analysis." *Energy Science & Engineering* 10, no. 8 (2022): 3154-3166. https://doi.org/10.1002/ese3.1210
[31] Nhede, Nicholas. "Solar to cover a quarter of global power by 2050." *Smart Energy International*. November 14, 2019.
[32] Global Solar Atlas. "Zimbabwe." *Global Solar Atlas*. Accessed June 25, 2021. https://globalsolaratlas.info/download/zimbabwe.
[33] Shuang-guo, N. I. U., and L. I. Shu-fang. "Research on 2MWp solar photovoltaic power generation technique." *Architecture Technology* 44, no. 7 (2013): 611-613.
[34] Michalsky, Joseph J. "The astronomical almanac's algorithm for approximate solar position (1950-2050)." *Solar Energy* 40, no. 3 (1988): 227-235. https://doi.org/10.1016/0038-092X(88)90045-X
[35] Marion, William F., and Aron P. Dobos. *Rotation angle for the optimum tracking of one-axis trackers*. No. NREL/TP-6A20-58891. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2013. https://doi.org/10.2172/1089596
[36] Duffie, John A., and William A. Beckman. *Solar engineering of thermal processes*. John Wiley & Sons, 2013. https://doi.org/10.1002/9781118671603
[37] Manzolini, Giampaolo, Andrea Giostri, Claudio Saccilotto, Paolo Silva, and Ennio Macchi. "Development of an innovative code for the design of thermodynamic solar power plants part B: Performance assessment of commercial and innovative technologies." *Renewable Energy* 36, no. 9 (2011): 2465-2473. https://doi.org/10.1016/j.renene.2011.02.003
[38] Zayed, Mohamed E., Jun Zhao, Wenjia Li, Ammar H. Elsheikh, Zhennan Zhao, A. Khalil, and Hao Li. "Performance prediction and techno-economic analysis of solar dish/stirling system for electricity generation." *Applied Thermal Engineering* 164 (2020): 114427. https://doi.org/10.1016/j.applthermaleng.2019.114427
[39] Mišljenović, Nemanja, Zvonimir Šimić, Danijel Topić, and Goran Knežević. "An algorithm for the optimal sizing of the PV system for prosumers based on economic indicators and the input data time step." *Solar Energy* 262 (2023): 111882. https://doi.org/10.1016/j.solener.2023.111882
[40] El Hamdani, Fayrouz, Sébastien Vaudreuil, Souad Abderafi, and Tijani Bounahmidi. "Determination of design parameters to minimize LCOE, for a 1 MWe CSP plant in different sites." *Renewable Energy* 169 (2021): 1013-1025. https://doi.org/10.1016/j.renene.2021.01.060
[41] Hernández-Moro, J., and Jose Manuel Martinez-Duart. "Analytical model for solar PV and CSP electricity costs: Present LCOE values and their future evolution." *Renewable and Sustainable Energy Reviews* 20 (2013): 119-132. https://doi.org/10.1016/j.rser.2012.11.082
[42] Zainali, Sebastian, Johan Lindahl, Johan Lindén, and Bengt Stridh. "LCOE distribution of PV for single-family dwellings in Sweden." *Energy Reports* 10 (2023): 1951-1967. https://doi.org/10.1016/j.egyr.2023.08.042
[43] Abdelhady, Suzan. "Performance and cost evaluation of solar dish power plant: sensitivity analysis of levelized cost of electricity (LCOE) and net present value (NPV)." *Renewable Energy* 168 (2021): 332-342. https://doi.org/10.1016/j.renene.2020.12.074