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Assessing the Impact of Soiling, Tilt Angle, and Solar Radiation on the Performance of Solar PV Systems

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This research examined the observed datasets and a theoretically derived model for estimating yearly optimum tilt angle (β), maximum incident solar radiation (H_{max}), clean gain indicator (CGI), and soiling loss indicator (SLI) at Mumbwa, Zambia, the Mediterranean Region, and low latitude locations across the globe. The cleaned tilted collector emerged as the best performing collector due to H_{max} and much higher energy gains compared with the soiled collector. CGI showed an appreciable performance of 0.4737% over -0.4708% on the SLI, indicating that soiling on the surface of photovoltaic (PV) modules significantly depreciates the overall performance of PV modules. Two established empirical models obtained from the literature were compared with the established theoretical model (β=φ). The result revealed that the two models overestimated the observed annual optimum tilt angle in this paper, simply because the models were developed with high latitude location datasets from the Asia continent. However, the newly established monthly and yearly global radiation indicator (GRI) models by the authors in their previous paper performed excellently in the selected representative cities in the Mediterranean region.

Keywords: Global tilted irradiance; Global horizontal irradiance; Soiling; Optimum tilt angle; Maximum incident solar radiation

Introduction

Assessing the optimum tilt angle, maximum incident solar radiation, and soiling effect of solar PV module performance is of great importance in order to accurately evaluate the solar PV module's performance and its lifetime. During the life of a solar PV module, the tilt angle and orientation of the module can affect its efficiency due to changing seasonal variations and soiling effects caused by environmental factors such as dust, pollution, windblown debris, and moisture. It is therefore essential to consider the optimum tilt angle and orientation of a solar PV module in order to ensure maximum efficiency and performance during its lifetime. To accurately assess the optimum tilt angle and orientation of a solar PV module, several factors must be taken into account, such as the site location [1], local climate [2], seasonal changes in temperature [3] and

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incident radiation [4], as well as soiling effects caused by dust [5] and other environmental factors [6].

As the tilt angle of a solar PV module increases, it will be exposed to more direct sunlight, which increases the maximum incident radiation on the module and therefore its performance and efficiency over the course of its lifetime [7]. During its lifetime, a solar PV module should be installed at an optimum tilt angle and orientation in order to maximize its efficiency and its return on investment [8,9,10]. The tilt angle and orientation of a solar PV module are thus important factors to consider when selecting a module for installation and should be taken into account when designing a solar PV system for a specific site location. In order to ensure that the installation of a solar PV module is optimized for maximum efficiency, these factors should be carefully considered and taken into account when selecting the tilt angle and orientation of the module.

This must be weighed against the additional costs associated with increasing the tilt angle of a solar PV module, such as additional costs for supporting structures, higher labour [11] and installation costs [12], and an increased risk of damage due to strong winds or snow loads [13]. Therefore, while it is important to consider the tilt angle and orientation of a solar PV module when selecting one for installation, this must be done in a balanced way to ensure that the costs are kept to a minimum [12] and that the efficiency of the module is maximized [11] while also ensuring that the risks of damage are minimized [14].

The selection of an optimal tilt angle and orientation for a solar PV module must be determined on a case-by-case basis [15], taking into account the local site conditions [16] and cost factors to ensure that the most effective and efficient selection is made for a given installation [17]. Generally, the selection of an optimal tilt angle and orientation for a solar PV module is an important consideration when installing one, as it can have a direct effect on the efficiency [18] and lifespan of the module [19]. Therefore, it is important to carefully weigh the potential costs associated with increasing the tilt angle of a solar PV module against the benefit of increased efficiency when making the decision [20].

Evaluating the optimum tilt angle, maximum incident solar radiation, and soiling effect of solar PV module performance in Mumbwa, Zambia, is an important part of understanding the potential of solar energy in this region in order to maximize its benefits in terms of cost efficiency [21], accessibility [22], and reliability of electricity production. By assessing these factors, researchers can determine the best time of year to install solar modules [23], the optimal tilt angle for maximum energy production [24], and gain insights into how frequently maintenance will be required due to soiling due to sand [25] and dust accumulation [26]. These assessments are key to determining the success of any solar energy initiatives in Mumbwa and ensuring that the citizens of Mumbwa are able to reap the full benefits of solar energy and have access to a reliable and cost-effective energy source.

The research conducted in Mumbwa is of paramount importance in helping to bring clean and reliable electricity to those who need it most. Furthermore, by studying the environmental and climatic conditions in Mumbwa, researchers can also determine what type of solar panels will be most appropriate for this region in order to maximize the efficiency of solar energy initiatives and ensure that these initiatives are cost-effective and capable of meeting the long-term energy needs of Mumbwa's citizens.

All of these findings can be used to inform policymakers on how best to use solar energy initiatives in Mumbwa, as well as which types of systems will provide the most reliable and cost-effective energy sources for the people living there. By properly assessing the environmental and climatic conditions in Mumbwa, as well as monitoring the successes of solar energy initiatives in the area, researchers can gain insight into how to best use solar energy to improve the lives of those living in Mumbwa and provide them with a sustainable source of electricity in a way that is both reliable and cost-effective. Ultimately, this research can have a huge impact on the quality of life for Mumbwa's citizens and provide them with a sustainable energy source that is reliable and cost-effective while also allowing them to benefit from the economic and social opportunities that come with having access to reliable electricity.

Numerous researchers have studied the effect of soiling and the optimum tilt angle on PV performance and found that soiling can reduce photovoltaic efficiency by up to 50% [11], while the optimum tilt angle can increase efficiency by up to 20% [12]. As such, maintaining clean solar panels and optimizing their tilt angle can have a significant positive impact on photovoltaic efficiency and should be taken into account when installing a solar PV system for maximum energy production. Indeed, these findings demonstrate that proper maintenance of solar modules can greatly improve the performance of photovoltaic systems and therefore should be a priority for those interested in maximizing their energy output.

This highlights the importance of having regular cleaning and maintenance routines for solar PV systems and making sure the solar modules are installed at an optimum tilt angle in order to capture the most energy from the sun and maximize the photovoltaic efficiency of the system over a given period of time. These findings suggest that careful attention must be paid to the cleanliness of PV modules and their tilt angle in order to maximize photovoltaic efficiency and energy production and to receive the most benefit from a solar photovoltaic system over the long run. Most studies revealed that soiling impacts negatively on the radiation and energy performance of PV systems and that it can be as high as 25% [18], which is substantial, and it could be argued that this underlines the importance of regular cleaning and maintenance of PV modules [25], whereas an optimal tilt angle enhances PV performance by increasing the amount of solar radiation absorbed and therefore increasing the efficiency of a PV system significantly [26].

The results of these studies clearly indicate the importance of ensuring regular cleaning and maintenance routines for solar PV systems, as well as making sure that the solar modules are installed at an optimum tilt angle in order to capture the most energy from the sun and maximize the photovoltaic efficiency of the system over a given period of time. These findings are further reinforced by other research studies conducted on the effects of tilt angle and soiling on photovoltaic efficiency and energy production, which have also revealed that soiling and the installation of the modules at an incorrect tilt angle can significantly reduce the efficiency of a PV system and could potentially lead to financial losses for the owners of the PV system due to lost energy production and increased operational costs. As such, it is important to note that regular maintenance of PV modules and their installation at an optimal tilt angle are both essential for maximizing photovoltaic efficiency and energy production over a given period of time.

In this paper, we have discussed the importance of ensuring proper maintenance routines and the installation angle of solar PV systems to ensure maximum photovoltaic efficiency and energy production over a given period of time. This is because soiling and the installation of modules at incorrect tilt angles can have a severe impact on energy production, leading to financial losses for owners of the PV system due to the reduced efficiency of their system as well as increased operational costs due to the need to regularly clean their system and the increased cost of energy production. In order to determine the effects of soiling and the optimum tilt angle on PV performance capacity, the global tilted irradiance as well as the global horizontal irradiance were analyzed in this study. Additionally, novel cleaning datasets were used to determine the global radiation indicator and energy gain/loss on monthly and yearly timescales in Mumbwa, Zambia.

As a result, different mathematical expressions developed in our previous paper were used to evaluate the optimum tilt angle and global radiation indicator used for evaluating maximum incident solar radiation in Mumbwa, Zambia, the Mediterranean region, and low latitude locations across the globe. The authors also developed an energy loss indicator for evaluating radiation levels and energy loss due to soiling, as well as an energy gain indicator for evaluating energy gain as a result of routine cleaning of PV systems.

Materials and Methods

Data Acquisition

The measured datasets such as soiled and clean global tilted irradiance using silicon irradiance sensors and global horizontal irradiance (W/m^2) employing thermopile pyranometers 1 & 2 in this paper were obtained from the Energy Sector Management Assistance Program of the World Bank Group for ZM_Solar_Mumbwa_IFC, station, Zambia (Latitude 15.08^{0}E, Longitude 27.00^{o}E, Elevation 1103m (https://energydata.info/dataset/zambia-solar-radiation-measurement-data). The obtained raw data (1-minute summarization interval values) were post-processed in order to obtain monthly mean values of soiled and clean global tilted irradiance (W/m^2) and global horizontal irradiance (W/m^2) values, as shown in Table 1.

Theoretical Model for Estimating Yearly Optimum Tilt Angles

The theoretical models for evaluating optimum tilt angles for low latitude locations in both the Northern and Southern Hemispheres developed in our previous paper [27] were used in this study.

$$\beta = \tan^{-1}\left[\frac{2\tan\phi}{1-\tan^{2}\phi}\right] \tag{1}$$

Equation (1) is the theoretical model developed in this study for evaluating the yearly optimum tilt angle for low latitude locations ($5.14^o \le \phi \le 0.0025^o$) on the Earth using only latitude as an input parameter. Where β is the optimum tilt angle, φ is the latitude of the location, and δ is the solar declination angle. Two empirical models for estimating yearly optimum tilt angles for high latitude locations [28, 29] were used to compare with the theoretical model developed in this study as presented in Table 2.

Table 1. Monthly mean values of clean and soil global tilted irradiance from the silicon irradiance sensor over global horizontal irradiance from the thermopile pyranometer (pyr1 and pyr2)

Month	ghi_pyr_1	ghi_pyr_2	Mean ghi_pyr	gti_clean	gti_soil
Jan-2018	277.77	278.03	277.9024	252.47	250.93
Feb-2018	191.03	191.08	191.0525	186.69	185.27
Mar-2018	213.86	214.14	213.9999	216.27	214.77
Apr-2018	225.23	225.39	225.3068	241.43	239.4
May-2018	208.17	208.25	208.2096	235.77	234.34
Jun-2018	208.36	208.45	208.4035	242.38	241.7
Jul-2018	187.1	187.23	187.1657	208.93	209.15
Aug-2017	249.15	249.7	249.4255	266.91	266.2
Sep-2017	265.08	265.57	265.3234	269.56	268.93
Oct-2017	240.72	241.04	240.8798	232.35	231.48
Nov-2017	218.39	218.63	218.5139	203.76	202.78
Dec-2017	227.07	227.29	227.1813	208.9	207.66
Mean	**225.99**	**226.23**	**226.1137**	**230.45**	**229.38**

Table 2. Evaluation of yearly optimum tilt angles for low latitude locations across the globe using the theoretical model developed in this study and other models from the literature

Country	Capital	Latitude	Longitude	Present study ($\beta=2\varphi$)	Talebizadeh et al. [30]	Jamil et al. [31]
Nigeria	Port Harcourt	4.4	7.17	8.8	10.19676	12.0394
Nigeria	Uyo	5.05	7.97	10.1	10.63902	12.47555
Nigeria	Calabar	4.95	8.32	9.9	10.57098	12.40845
Nigeria	Yenegao	4.93	6.26	9.86	10.557372	12.39503
São Tomé und Príncipe	São Tomé (capital)	0.33	6.73	0.66	7.427532	9.30843
São Tomé und Príncipe	Santana	0.25	6.74	0.5	7.3731	9.25475
São Tomé und Príncipe	Trindade	0.29	6.81	0.58	7.400316	9.28159
Gabon	Libreville	0.42	9.47	0.84	7.488768	9.36882
Gabon	Oyem	1.59	11.57	3.18	8.284836	10.15389
Gabon	Moanda	1.53	13.24	3.06	8.244012	10.11363
Gabon	Mouila	1.87	11.05	3.74	8.475348	10.34177
Uganda	Kampala	0.34	32.58	0.68	7.434336	9.31514
Uganda	Nansana	0.36	32.52	0.72	7.447944	9.32856
Uganda	Kira	0.39	32.63	0.78	7.468356	9.34869
Lake Victoria	Kampala	0.34	32.58	0.68	7.434336	9.31514
Lake Victoria	Kira Town	0.39	32.63	0.78	7.468356	9.34869
Lake Victoria	Kisumu	0.09	34.76	0.18	7.264236	9.14739
Lake Victoria	Nkozi	0.0025	32.014	0.005	7.204701	9.0886775

Lake Victoria	Bukoba	1.33	31.8	2.66	8.107932	9.97943
Kenya	Nairobi	1.29	36.82	2.58	8.080716	9.95259
Kenya	Namanga	2.55	36.78	5.1	8.93802	10.79805
Kenya	Kibwezi	2.41	37.96	4.82	8.842764	10.70411
Somalia	Mogadishu	2.05	45.31	4.1	8.59782	10.46255
Somalia	Aadan Yabaa	3.78	46.25	7.56	9.774912	11.62338
Malaysia	Kuala Lumpur	3.13	101.68	6.26	9.332652	11.18723
Malaysia	Kuching	1.55	110.35	3.1	8.25762	10.12705
Malaysia	Johor Bahru	1.49	103.74	2.98	8.216796	10.08679
Singapore	Singapore	1.35	103.81	2.7	8.12154	9.99285
Singapore	Hougang	1.36	103.88	2.72	8.128344	9.99956
Singapore	Yishun	1.43	103.83	2.86	8.175972	10.04653
Indonesia	Batam	1.13	104.05	2.26	7.971852	9.84523
Indonesia	Medan	3.59	98.67	7.18	9.645636	11.49589
Indonesia	Makassar	5.14	119.43	10.28	10.700256	12.53594
Colombia	Bogota	4.71	74.07	9.42	10.407684	12.24741
Colombia	Cali	3.45	76.53	6.9	9.55038	11.40195

Mathematical Expressions for Computing Maximum Incident Solar Radiation under Clean and Soiled PV Modules

The following mathematical expressions were developed so as to evaluate the global radiation indicator (GRI) for clean and soiled global tilted irradiance in the Mediterranean region, as presented in Table 3.

$$GRI = \frac{Clean/Soiled \text{ global tilted irradiance (H clean/H soiled)}}{\text{global hoizontal irradiance (H pyr1/H pyr2/mean H pyr1 \& 2)}} \qquad (2)$$

$$Clean\ global\ tilted\ irradiance\ (H\ clean) = 1.024 * H\ pyr1 \qquad (3)$$

$$Clean\ global\ tilted\ irradiance\ (H\ clean) = 1.019 * H\ pyr2 \qquad (4)$$

$$Clean\ global\ tilted\ irradiance\ (H\ clean) = 1.0235 * mean\ H\ pyr1\ \&\ pyr2 \qquad (5)$$

$$Soiled\ global\ tilted\ irradiance\ (H\ Soiled) = 1.0193 * H\ pyr1 \qquad (6)$$

$$Soiled\ global\ tilted\ irradiance\ (H\ Soiled) = 1.0183 * H\ pyr2 \qquad (7)$$

$$Soiled\ global\ tilted\ irradiance\ (H\ Soiled) = 1.0188 * mean\ H\ pyr1\ \&\ pyr2 \qquad (8)$$

Table 3. Maximum incident solar radiation under clean and soiled Silicon PV module

Country	**city**	**Lat**	**Long**	**H**	**H tilted clean using pyr1**	**H tilted clean using pyr2**	**H tilted clean using mean pyr1 & pyr2**	**H tilted soiled using pyr1**	**H tilted soiled using pyr2**	**H tilted soiled using mean pyr1 & pyr2**
Egypt	Luxor	25.69	32.64	261.93	268.21	266.90	268.08	266.98	266.72	266.85
Morocco	Smara	26.73	11.67	250.44	256.45	255.20	256.33	255.28	255.03	255.15
Egypt	Sharm Sheikkh	27.86	34.36	240.12	245.88	244.68	245.76	244.75	244.51	244.63
Morocco	Agadir	30.41	9.6	241.51	247.31	246.10	247.19	246.17	245.93	246.05
Libya	Sabha	30.63	18.35	239.66	245.41	244.21	245.29	244.28	244.04	244.16
Egypt	Alexandria	31.2	29.92	217.96	223.20	222.11	223.09	222.17	221.95	222.06

Palestine	Gaza	31.41	34.31	231.30	236.86	235.70	236.74	235.77	235.54	235.65
Libya	Tripoli	32.9	13.19	226.32	231.75	230.62	231.63	230.68	230.46	230.57
Syria	Damascus	33.51	36.28	226.20	231.63	230.50	231.52	230.57	230.34	230.45
Algeria	Mecheria	33.55	0.28	223.18	228.54	227.42	228.43	227.49	227.27	227.38
Lebanon	Beirut	33.88	35.5	212.86	217.97	216.90	217.86	216.97	216.76	216.86
Cyprus	Nicosia	35.16	33.38	204.97	209.89	208.87	209.79	208.93	208.72	208.83
Morocco	Larache	35.18	6.15	198.13	202.88	201.89	202.78	201.95	201.75	201.85
Greece	Heraklion	35.32	25.14	197.08	201.81	200.83	201.72	200.89	200.69	200.79
Syria	Latakia	35.52	35.8	200.68	205.50	204.49	205.40	204.55	204.35	204.45
Tunisia	Tunis	35.41	10.18	209.73	214.76	213.71	214.66	213.78	213.57	213.67
Malta	Vallella	35.89	14.51	199.06	203.83	202.84	203.73	202.90	202.70	202.80
Tunisia	Bizerte	37.27	9.86	185.83	190.29	189.36	190.20	189.42	189.23	189.33
Spain	Seville	37.38	5.98	183.16	187.56	186.64	187.47	186.70	186.52	186.61
Turkey	Isparta	37.76	30.55	195.34	200.03	199.06	199.93	199.11	198.92	199.02
Italy	Marsala	37.8	12.44	187.80	192.31	191.37	192.22	191.43	191.24	191.33
Greece	Anthen	37.97	23.73	189.08	193.62	192.67	193.52	192.73	192.54	192.63
Turkey	Bursa	40.18	29.06	169.82	173.90	173.05	173.81	173.10	172.93	173.02
Spain	Madrid	40.4	3.7	181.42	185.78	184.87	185.69	184.93	184.74	184.83
Albania	Vlore	40.46	19.49	176.78	181.03	180.14	180.94	180.20	180.02	180.11
Greece	Thessaloniki	40.63	22.94	174.23	178.41	177.54	178.33	177.59	177.42	177.51
Italy	Naples	40.83	14.27	175.74	179.96	179.08	179.87	179.13	178.96	179.04
Montenegro	Podgoria	42.47	19.26	157.41	161.19	160.40	161.11	160.45	160.29	160.37
Bosnia & Herzegovina	Sarajevo	43.51	18.41	150.10	153.71	152.96	153.63	153.00	152.85	152.93
Monaco	Monaco	43.73	7.42	163.33	167.25	166.43	167.17	166.48	166.32	166.40
Italy	Florence	43.77	11.26	158.34	162.14	161.35	162.06	161.40	161.24	161.32
Italy	Milan	45.46	9.19	157.06	160.83	160.05	160.76	160.10	159.94	160.02
France	Lyon	45.76	4.84	153.00	156.68	155.91	156.60	155.96	155.80	155.88
Croatia	Zagreb	45.81	15.98	140.13	143.49	142.79	143.42	142.83	142.69	142.76
Slovenia	Ljubljana	46.05	14.51	136.76	140.05	139.36	139.98	139.40	139.27	139.34

Energy Gain/Loss for Clean and Soiled Global Tilted Irradiance (MJm^{2}day^{-1})

Mathematically, the percentage gain or loss is the availability of global tilted irradiance of solar PV over global horizontal irradiance PV modules as presented in Table 4 and Fig. 1. This is evaluated using the following equations:

$$\text{Percentage gain (\%)} = \left(\frac{H_T \langle \beta = tited \rangle}{H \langle \beta = 0 \rangle} - 1 \right) \times 100 \qquad (9)$$

$$\text{Percentage loss (\%)} = \left(1 - \frac{H_T \langle \beta = tited \rangle}{H \langle \beta = 0 \rangle} \right) \times 100 \qquad (10)$$

Table 4. Monthly mean values of energy gain or loss under clean and soil global tilted irradiance from the silicon irradiance sensor over global horizontal irradiance from the thermopile pyranometer (pyr1 and pyr2)

Month	Clean tilted H vs H pyr1	Clean tilted H vs H pyr2	Soil tilted H vs H pyr1	Soil tilted H vs H pyr2	Clean tilted H vs /mean H pyr	Soil tilted H vs /mean H pyr	Clean Gain Index	Soiling loss Index
Jan-2018	-9.109	-9.195393	-9.66237	-9.7478	-9.1525	-9.7051	0.6120	-0.6083
Feb-2018	-2.268	-2.294056	-3.01528	-3.0411	-2.2811	-3.0282	0.77045	-0.7646
Mar-2018	1.1283	0.997946	0.424425	0.29496	1.06309	0.35965	0.7009	-0.6960
Apr-2018	7.1942	7.117796	6.293023	6.21725	7.15599	6.25512	0.8478	-0.8407
May-2018	13.256	13.21311	12.57008	12.5275	13.2345	12.5488	0.6093	-0.6056
Jun-2018	16.33	16.27633	16.00354	15.9501	16.3031	15.9768	0.2814	-0.2806
Jul-2018	11.668	11.59292	11.78406	11.7086	11.6306	11.7463	-0.1035	0.1036
Aug-2017	7.1291	6.894265	6.841287	6.60705	7.01157	6.72404	0.2694	-0.2687
Sep-2017	1.6896	1.500913	1.452322	1.26405	1.59518	1.3581	0.2339	-0.2334
Oct-2017	-3.475	-3.604361	-3.83891	-3.9674	-3.5399	-3.9032	0.3781	-0.3766
Nov-2017	-6.698	-6.801507	-7.14813	-7.251	-6.7499	-7.1996	0.4846	-0.4823
Dec-2017	-8.001	-8.091241	-8.54972	-8.6397	-8.046	-8.5947	0.6003	-0.5967
Mean	**2.4036**	**2.300561**	**1.929528**	**1.82688**	**2.35207**	**1.87817**	**0.4737**	**-0.4708**

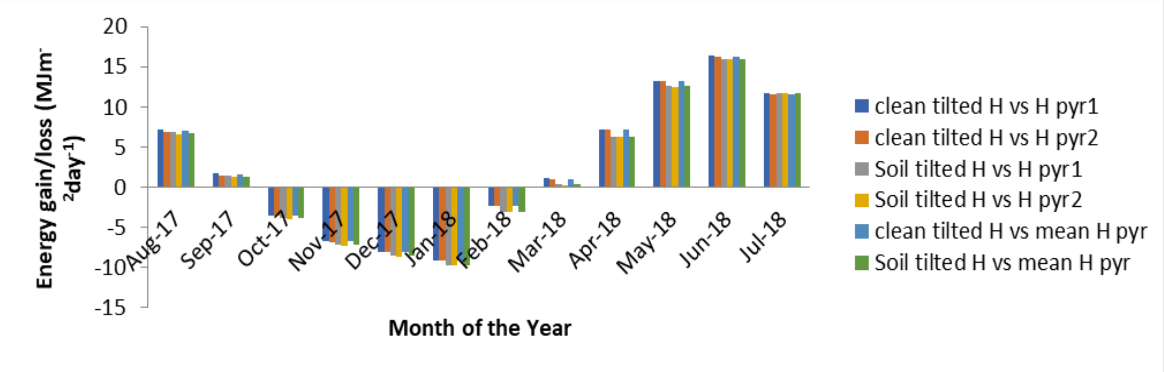

Fig. 1. Energy Gain/Loss versus months of the year under clean and soil global tilted irradiance from the silicon irradiance sensor over global horizontal irradiance from the thermopile pyranometer (pyr1 and pyr2)

Clean Gain Indicator (CGI) and Soiling Loss Indicator (SLI)

Mathematically, the clean gain indicator (CGI) and soiling loss indicator (SLI) for the silicon irradiance sensor in Mumbwe, Zambia, as presented in Table 4 and Fig. 2, are evaluated using the following:

$$Clean\ gain\ indicator = \frac{Soiled\ H - clean\ H}{clean\ H} * \frac{100}{1} \tag{11}$$

$$Soiled\ gain\ indicator = \frac{Clean\ H - Soiled\ H}{Soiled\ H} * \frac{100}{1} \tag{12}$$

where soiled H represents soiled global tilted irradiance, clean H represents clean global tilted irradiance.

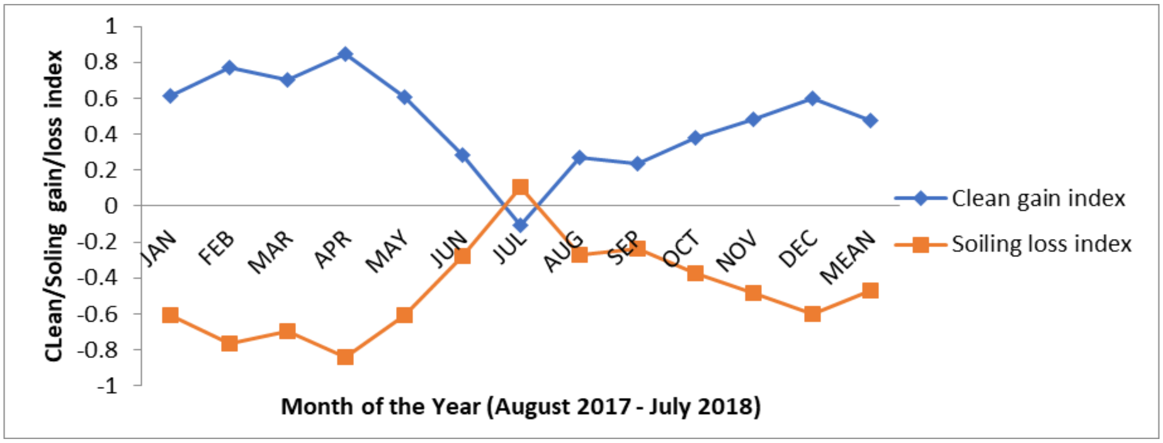

Fig. 2. Clean/Soiling gain/loss index for Mumbwa, Zambia

Results and Discussion

Table 1 presents the monthly and yearly global horizontal irradiance for pyr1 and pyr2, clean and soiled global tilted irradiance, for Mumbwe, Zambia. The data in Table 1 showed that the monthly and yearly global horizontal irradiance was higher in Pyr2 than in Pyr1, but both clean and soiled global tilted irradiance were generally lower than the global horizontal irradiance values. Furthermore, the data indicated that there was a decrease in both clean and soiled global tilted irradiance from Pyr1 to Pyr2 for all months, though the difference was more pronounced for the soiled global tilted irradiance than for clean global tilted irradiance. This suggests that the orientation and tilt of Pyr1 were better suited to capture sunlight than those of Pyr2, as the latter experienced reduced irradiance levels across both clean and soiled conditions.

As a result, the data presented in Table 1 indicates that the orientation and tilt of Pyr1 were better suited to capture sunlight than those of Pyr2, providing an insight into how the tilt and orientation of PV modules can affect their performance in terms of capturing solar irradiance and thus their potential to produce electricity. This understanding of the importance of tilt and orientation when installing PV modules is an important aspect to consider, as it can directly affect their performance and thus energy output. This finding is especially important for the installation and design of PV systems in different regions, as it highlights the importance of accounting for orientation and tilt when considering which PV modules to install in order to maximize energy output from PV systems in different environments.

It could be seen clearly that clean global tilted irradiance yielded higher radiation compared to soiled global tilted irradiance and global horizontal irradiance for both Pyr1 and Pyr2 which implies that the orientation and tilt of PV panels have a direct impact on the amount of solar irradiance they are able to capture, resulting in an increased electrical energy output This is further evidenced by the fact that Pyr1 generated more electrical energy in clean global tilted irradiance than Pyr2, suggesting that not only tilt but also orientation have an effect on the performance of PV panels when capturing solar irradiance and producing electricity. This validates the report found in the literature that an optimum tilt angle and a clean PV system perform better than horizontally mounted PV and soiled PV systems [32]. This finding is especially significant in terms of PV system installation and design, as it indicates that orientation and tilt are critical when determining which PV modules to install in order to maximize energy output.

From Table 2, it can be seen that the yearly optimum tilt angle obtained from literature [33] overestimates optimum tilt angles compared to the latitude of the observed values developed from $\beta=2\varphi$ in the study location. This suggests that the optimum tilt angle for an inclined surface should be adjusted according to geographic latitude [34] and the orientation of a module to achieve maximum performance [35]. Furthermore, the findings of this research highlight the need for clean PV modules in order to obtain maximum energy output since the angle of incidence of light is directly related to the energy output from a PV module. As such, the findings of this research provide useful information that can be used by PV system installers and designers to determine the optimum tilt and orientation for a given installation in order to optimize the energy yield and increase overall efficiency [36]. Furthermore, the optimal tilt angle should be re-evaluated periodically as factors such as seasonal weather patterns, soiling, and dust accumulation can lead to a reduction in the energy output of the PV system if they are not taken into account in order to maximize the performance of the system. Additionally, it is important to consider other factors that may affect the performance of the PV module, such as cloud cover and snow accumulation, as these can significantly reduce the energy output from a system if they are not taken into consideration when deciding on the optimal tilt angle and orientation for a PV system. Thus, this research indicates that there are a number of factors to consider when determining the optimal tilt angle and orientation for a PV system in order to maximize its energy output, maximize its overall efficiency, and ensure that it continues to yield the maximum possible energy output over time. In general, this research highlights the importance of considering a variety of factors when deciding on the optimal tilt angle and orientation for a PV system in order to maximize its efficiency.

From Table 3, it can be seen that the global horizontal irradiance and maximum incident solar radiation estimated using equations 2–8 vary considerably from one site to another, even for locations with equivalent latitude angles, which further emphases the importance of taking all relevant factors into consideration when determining the optimal tilt angle and the orientation of a PV system. These results demonstrate the importance of taking location-specific characteristics [37], such as local climate [38] and cloud cover [39], into account when deciding on the optimal tilt angle and orientation for a PV system in order to maximize its efficiency and ensure that it continues to yield the maximum possible energy output over time. The results of this research indicate that the optimal tilt angle and orientation of a PV system should be determined based on the combination of multiple factors such as global horizontal irradiance [40], latitude [41], maximum incident solar radiation [42], and cloud cover [43].

In addition to latitude, orientation, and tilt angle, the intensity of cloud cover [44] and snow accumulation [45] should also be taken into consideration when deciding on the optimal tilt angle and orientation for a PV system in order to maximize its efficiency and ensure that it continues to yield the maximum possible energy output over time. Furthermore, the results of this research provide a valuable insight into the importance of accurately assessing the local climate conditions and taking all relevant factors into consideration when deciding on the optimal tilt angle and orientation for a PV system in order to maximize its efficiency and ensure that it continues to yield the maximum possible energy output over time.

For instance, although Bujumbura and Yaounde reported equivalent latitudes (3.61 °N and 3.84 oN, respectively), their yearly global solar radiation registered 194.4 W/m^2 and 184.3 W/m2, respectively indicating that Bujumbura receives significantly more solar radiation than Yaounde due to the different cloud cover [45], and snow accumulation factors [46] demonstrating that these are important elements to consider when making decisions regarding PV systems in different locations. The study further showed that even in locations with similar latitudes, other local climate factors such as cloud cover and snow accumulation could significantly affect the performance of a PV system and, therefore, should be taken into consideration in order to ensure that the PV system continues to yield the maximum possible energy output over its lifetime. Similarly, Monaco and Sarajevo recorded equivalent latitudes (43.73 °N and 43.51 oN, respectively), and their yearly global solar radiation recorded 163.33 W/m^2 and 150.1 W/m2, respectively demonstrating that even though the two locations share the same latitude, Monaco still receives significantly more solar radiation due to a combination of different local factors [47] , showing again how important it is to consider other climate factors in addition to latitude when deciding on the optimal tilt angle and orientation for a PV system in order to maximize its efficiency and ensure that it continues to yield the maximum possible energy output over time.

These results indicate that while latitude is an important factor to consider when determining the optimal tilt angle and orientation for a PV system, other local climate factors such as cloud cover and snow accumulation must also be taken into account in order to ensure that the system continues to perform at peak capacity and yield the maximum possible energy output over its lifetime. These findings are further evidence that latitude alone is not enough to accurately predict the energy output of a PV system and that an analysis of all local climate factors is necessary in order to accurately determine the optimal tilt angle and orientation for a given PV system in order to ensure that the system continues to yield the maximum possible energy output over its lifetime. Other relevant climate factors must also be taken into consideration when designing and installing a PV system in order to accurately predict the energy output and determine the optimal tilt angle and orientation of a PV system.

Higher annual energy gains were reported for clean global tilted irradiance using pyr1 (2.403%), pyr2 (2.3006%), and 2.35207% for mean pyr1 and pyr2 compared to 1.929528%, 1.82688%, and 1.87817% recorded for soiled global tilted irradiance using pyr1, pyr2, and mean pyr1 and pyr2 respectively, as presented in Table 4 and Fig. 1. These findings show that the optimal tilt angle and orientation of a PV system should not be based solely on latitude, but also on other climate factors such as cloud cover, snow accumulation, and global tilted irradiance. These findings demonstrate the importance of accurately determining the optimal tilt angle and orientation of a PV system in order to ensure that the system is able to yield the maximum possible energy output over its lifetime. In addition to latitude, it is also important to consider other local climate factors when designing and installing a PV system, as they can greatly affect the amount of energy the system is able to generate.

These results are lower than the annual energy for an annual timescale of 65% reported by Jamil et al. [31] and 4.39% for a temperate climate for an annual optimum tilt in comparison with a horizontal surface Jamil et al. [48]. These findings indicate that the determination of the optimal tilt angle and orientation of a PV system must take into account local climate conditions, such as cloud cover, snow accumulation, and global tilted irradiance, to ensure that the system is able to generate the maximum amount of energy over its lifetime. In general, the optimal tilt angle and orientation of a PV system must be determined accurately in order to maximize its energy output over its lifetime. For example, a PV system in the northern hemisphere with a tilt angle of 15° and an azimuth angle of 180° will provide a higher energy yield than one with an azimuth angle of 135° due to seasonal differences in radiation. These differences can be attributed to the fact that the impact of soiling on PV in Jodhpur and Bangalore, India, is higher in Mumbwe, Zambia, located in Sub-Saharan Africa, because of its proximity to an arid environment.

The findings suggest that the determination of the optimal tilt angle and orientation for a PV system is essential to ensuring that it performs optimally over its lifetime and that, depending on the location of the system, soil and environmental conditions should be taken into consideration when calculating the optimal tilt angle and orientation. From Table 4, it can be seen that the clean energy indicator yielded appreciable values from January to December and annually (0.4737%) except the month of July, 2018 that reported a negative value of -0.1035%; whereas, the soiling loss indicator vehemently yielded excepted negative values throughout the months except the month of July, 2018 that recorded a positive value of 0.1036% as shown in Fig. 2.

This indicates that in Mumbwe, Zambia, the soiling loss has a more significant effect on the performance of PV systems than the impact of seasonal variations in radiation when compared to Jodhpur and Bangalore, India. The main reason for this difference can be attributed to the presence of an arid climate in Mumbwe, Zambia, which leads to a high level of soiling due to dust and other airborne particles, thus reducing the efficiency of the PV system significantly when compared to the other locations. Thus, confirming that soiling impacts negatively on PV performance as reported by numerous studies worldwide [49, 50, 51]. The findings of this study support the notion that regular cleaning of solar panels is a necessity in Mumbwe, Zambia, for optimal performance. This is in stark contrast to Jodhpur and Bangalore, India, where soiling did not appear to have a major effect on PV performance due to the lower levels of airborne particles present in their respective climates. As such, the data collected from Mumbwe, Zambia, serves as evidence that the environment can have a profound impact on PV performance and therefore should be taken into account when installing a solar system in any given region. The results from the study conducted in Mumbwe, Zambia, show that the environment can have a significant impact on PV performance and, as a result, regular cleaning of solar panels is essential in order to ensure optimal performance in the region and should be taken into consideration when planning a solar system installation. This research has revealed the importance of regular cleaning of solar panels, particularly in Mumbwe, Zambia, where airborne particles can have a significant effect on PV performance.

CONCLUSIONS

The orientation and tilt of PV modules can affect their performance in terms of capturing solar irradiance and thus their potential to produce electricity. This research validates the report that an optimum tilt angle and a clean PV system perform better than horizontally mounted PV and soiled PV systems. The optimal tilt angle and orientation for a PV system should be determined based on multiple factors such as global horizontal irradiance, latitude, maximum incident solar radiation, and cloud cover. This research provides insight into the importance of accurately assessing local climate conditions and taking all relevant factors into consideration when deciding on the optimal tilt angle and orientation for a PV system. The following represents the major findings from this study:

1. The cleaned tilted collector emerged as the best performing collector due to higher H_{max} and energy gain, while CGI showed an appreciable performance of 0.4737% over SLI.
2. As a result of adjusting PV cleaning schedules for the greatest return on investment in Mumbwe, Zambia, CGI increases noticeably, by about 0.4737%.
3. Due to the fact that the models were generated using high latitude location datasets from the Asian continent, the results showed that the two models taken from the literature overestimated the observed yearly optimum tilt angle in this paper.
4. The maximum incident solar radiation values were significantly higher than the global horizontal irradiance (H) as expected in all locations investigated, demonstrating excellent performance of the newly established monthly and yearly global radiation indicator (GRI) coefficient models used for evaluating maximum incident solar radiation in the Mediterranean region and other low latitude locations around the world.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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