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Performance Improvement of Aerosols Impacted Concentrated Solar Power in Arid Regions: Case Study of Solar Power Tower Hybridization With Wind Turbines in Kuwait

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ABSTRACT

The main objective of the current work is to assess the hybridization of a solar power tower's with wind turbines and the potential of this integration to compensate the energy losses caused by aerosols attenuation of the reflected irradiance of the solar field. The combined solar power tower and wind turbines configurations are assessed over the range of 60-100 MW. A maximum reduction of 6.8 % in the annual energy generation is found in the standalone solar power tower when the aerosols are adopted. The integration of wind turbines has a limited effect in the compensation of the energy loss due to the aerosols effect on the solar field, however, it has a major role in the decrease of the LCOE.

Keywords: Solar power tower, Levelized cost of energy, Aerosols, Wind, Hybridization.

NONMENCLATURE

Abbreviations	
AEG	Annual energy generation
AOD	Aerosols optical depth
CAPEX	Capital expenditures
CSP	Concentrated solar power
DNI	Direct normal irradiance
KISR	Kuwait institute of scientific research
LCOE	Levelized cost of energy
OPEX	Operation expenditures
SM	Solar multiple
SPT	Solar power tower
TAY	Typical aerosols year
TES	Thermal energy storage
TMY	Typical metrological year
Symbols	
A	Attenuation percentage
S	Slant range

1. INTRODUCTION

Solar Power Tower (SPT) technology coupled with Thermal Energy Storage (TES) has lately emerged as one of the most efficient Concentrated Solar Power (CSP) types as it offers high concentration levels, and thus higher solar to electrical conversion rates, Capacity Factor (CF), Annual Energy Generation (AEG) and lower Levelized Cost of Energy (LCOE). However, the power availability is still far from being 24/7 available and the LCOE is much higher than that of other more mature renewable energy technologies, e.g. wind turbines. On the other hand, despite lower LCOE values of the wind turbines, the technology suffers the highest levels of fluctuations for a renewable technology [1].

This work aims at obtaining the best return on investment of a CSP-Wind plant configuration that avoids the large solar field and TES sizes and at the same time avoids the wind power fluctuation. A techno-economic assessment which targets a higher AEG and a lower LCOE is carried out by varying two important key design parameters that contribute the most in the elevation of the capital costs and LCOE, i.e. Solar Multiple (SM) and TES, while varying the number of wind turbines.

2. SYSTEM DESCRIPTION AND HYBRIDIZATION

The SPT's solar field consists of thousands of mirrors, mostly positioned in a circular field, with the aim of focusing the Direct Normal Irradiance (DNI) of the sun on a common receiver mounted on the top of a tower. A molten salt heat transfer fluid passes at the receiver and gets heated by the sun concentration and then gets either stored in the TES for later usage or directly passes to the power cycle (here the Rankine cycle) to produce the required steam to drive the generator's turbine. The

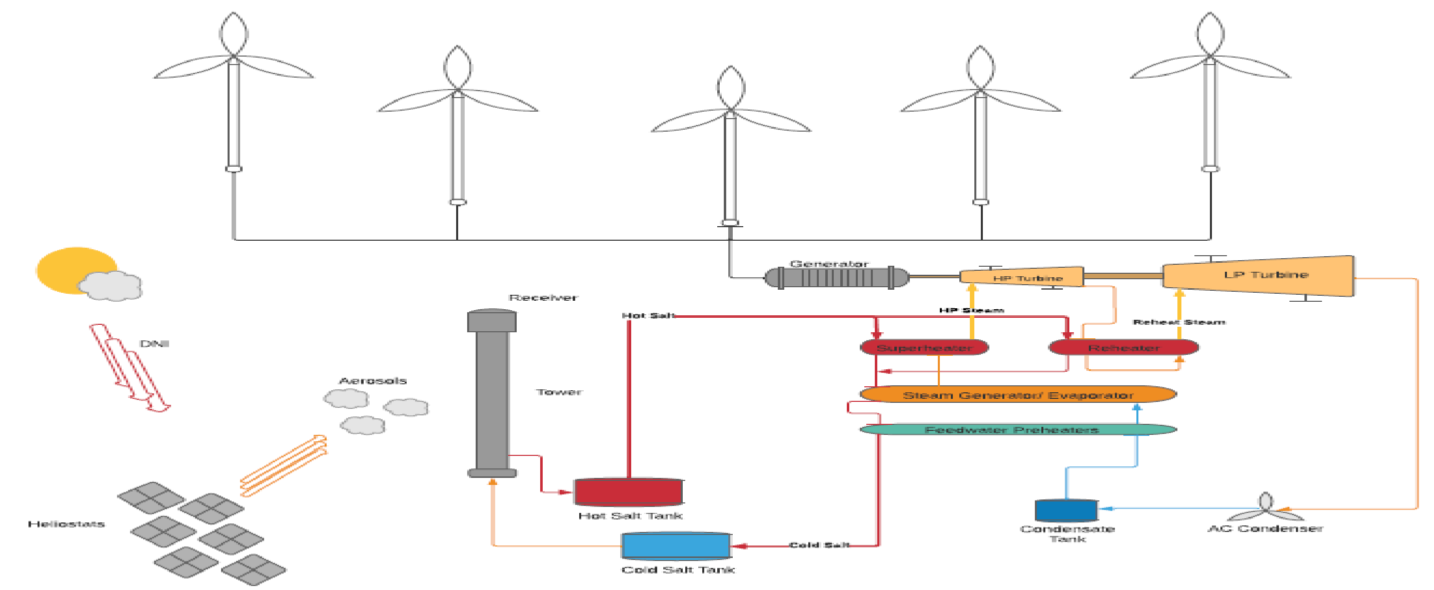


Fig. 1. Schematic of the CSP-Wind hybridization based on SPT.

hybridization is realized using wind turbines directly connected to the 50-90 MW SPT's generator as shown in Figure 1.

The proposed hybridization is simulated in a remote arid region in Kuwait's Shagaya Renewable Energy Park (SREP) where a 50 MW Parabolic Trough Collector (PTC) plant, 10 MW wind turbines and 10 MW PV already operate. Significant solar and wind resources have already been reported in the referred location in other works [2], [3] which promotes further solar-wind collocating potential. No technical or energy price data have been revealed of the operating PTC in the site. Sultan et al. [4] has simulated a 50 MW PTC in SREP and found that the lowest LCOE is 15.07 ¢/kWh at 16h of TES and a SM of 3.2. A lower LCOE of 12.87 ¢/kWh has been found by Alfailakawi et al. [5] who simulated a 50 MW SPT in the same location.

In addition, as reported in [2], the energy generation of the five operating 2-MW wind turbines in SREP is 38.25 GWh with a capacity factor of 43.7% averaged over the two years operation period. No LCOE prices have been revealed as of yet.

3. MATERIAL AND METHODS

3.1. SPT Model Performance Simulation

As a baseload power source, the SPT has been first optimized within a parametric analysis where TES is varied from 0-18h and the SM is varied from 1-4 with 1h and 0.2 step sizes for the TES and SM, respectively. The parametric analysis targets an optimal TES-SM configuration represented by the lowest LCOE value. The inclusion of the aerosols effect on the reflected irradiance from the reflectors towards the receiver are described by a Typical Aerosols Year (TAY). This has been prepared based on Finkelstein-Schaffer statistics for 5 aerosols years for the same period of the Typical Metrological Year (TMY) and this has been used as weather file for the SPT model in the same location:

$$FS = \frac{1}{N}\sum_{i=1}^{N} \left| CDF_{m(di)} - CDF_{y,m(di)} \right| \qquad (1)$$

where $CDF_{m(di)}$ is the cumulative distribution function of the long term of the indices (d_i) daily mean, $CDF_{y,m(di)}$ is the cumulative distribution function of the short term in month *m* and year *y* and *N* is the number of days in the corresponding month (FS normalization for months with different number of days [6]).

The daily AOD values are then integrated into the SAM simulation tool [7] through a Radiative Transfer Model (RTM), i.e. the Polo Model [8]:

$$\begin{aligned} a &= 3.13\,AOD^3 - 1.9\,AOD^2 + 1.6\,AOD - 0.133 \\ b &= -14.74\,AOD^3 + 2.49\,AOD^2 - 11.85\,AOD + 0.544 \\ c &= 28.32\,AOD^3 - 7.57\,AOD^2 + 48.74\,AOD + 0.371 \\ d &= -2.61\,AOD^3 + 3.70\,AOD^2 - 2.64\,AOD + 0.179 \end{aligned} \qquad (2)$$

The RTM has the ability to integrate the aerosols effect in addition to the already existing distance effect between the reflectors and receiver, i.e. the slant range (S). As a result, the coefficient of the solar field's attenuation function are obtained as follows [9]:

$$A(\%) = aS^3 + bS^2 + cS + d \qquad (3)$$

where *A* is the solar field's attenuation percentage.

The annual averaged AOD value used in the Polo model is a result of the site adapted 5 years long aerosols data which has been acquired from the Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA-2). The site adaptation has been realized by using the MERRA-2 data along with a one year of ground measured data from the AERONET station in the case study location. The annual averaged AOD value of the site adapted TAY is found to be equal to 0.3205 as illustrated in Table 1. It is worth mentioning that the TMY used in this work for the SPT performance model in the SAM software has been provided by the Kuwait Institute for Scientific Research (KISR). This TMY is also a site adapted weather file with the assistance of ground measured data in the case study location.

Table 1
SPT technical parameters

	parameter	description
System Design	Solar multiple	1 to 4 (with a step of 0.2)
	Irradiation at design	700 W/m^2
	HTF hot temperature	574 °C
	HTF cold temperature	290 °C
	Full load hours of storage	0-18 (with a step of 1 h)
Tower and Receiver	Tower height	Obtained from optimization (SolarPILOT)
	Receiver diameter	Obtained from optimization (SolarPILOT)
	HTF type	Molten Salt (60% $NaNO_3$ + 40% KNO_3)
	Receiver flow pattern	Configuration 2
Heliostats Field	Layout configuration	Always optimize
	Heliostats length	12.2 m
	Heliostats width	12.2 m
Atmospheric attenuation	Annual averaged AOD	0.3205
	Polynomial coefficient 0	-0.0037298
	Polynomial coefficient 1	0.154
	Polynomial coefficient 2	-0.0348
	Polynomial coefficient 3	0.0028768
Power Cycle	Condenser type	Air-cooled
	Ambient temperature at design	31.6 °C
Thermal Energy Storage	Storage type	Two tanks
	Tank height	20 m

The SPT, with whatever optimal TES-SM configuration found from the parametric analysis for each capacity, is considered as a baseload of the model and does not go below 50 MW, while the WT is an incremental source of energy with an increasing range starting from 10 – 50 MW. A no aerosols scenario is simulated and considered as a perfect rated capacity scenario and targeted as the 100 % reference point.

3.2. *Wind Turbines Integration*

The combined SPT-Wind model has been also simulated in the SAM software environment. First, each technology was simulated individually. Then, both performance models are combined into a hybrid SPT-WT model where outputs, such as AEG, CF and LCOE are calculated for the entire system. The AEG and CF are simply aggregated for the combined case, while the LCOE calculation procedures sums up both individual cases' Capital Expenditures (CAPEX) and Operational Expenditures (OPEX) and then calculates the LCOE as follows [10]:

$$LCOE = \frac{CAPEX_0 + \sum_{t=1}^{N} \frac{OPEX_t}{(1 + i)t}}{\sum_{t=1}^{N} \frac{Production_t}{(1 + i)t}} \tag{4}$$

where $Production_t$ is the plant production in year *t* (AEG). Table 2 shows the technical parameters of the pilot 5 WT in SREP.

Table 2
Wind turbines technical parameters.

	parameter	description
Turbine	Type	Siemens-Gamesa G97
	Capacity	2 MW (each)
	Hub height	78.98 m
	Rotor diameter	97 m
Configuration	No. of turbines	5-25
	Distance between turbines (m)	330

After determining the optimal SPT configuration for each plant capacity, the integration of different number of turbines is carried out. The minimum considered WT capacity is 10 MW, which represents the 5 WT as in the pilot plant of SREP. The total number of simulations of the combined cases is only 5 as it ranges from 60 MW to 100 MW in a way that the baseload is always a minimum of 50 MW SPT and the incremental routine occurs with a step size of 10 MW while the maximum of the combined cases does not exceed 100 MW.

4. RESULTS AND DISCUSSION

4.1. SPT Validation

Initially, the 50 MW SPT model used in this work has been validated. The validation process has been accomplished using data derived from Soomro et al. [11] as it is one of the few published data of a similar model and capacity. The results have been compared for two locations and have produced a maximum deviation of 8.8% (found in the LCOE) and this is most probably due to the differences in the weather files and the possible differences in the financial assumptions used in the simulations processes. Table 2 illustrates the comparison of both simulations.

Table 3
The validation process of the SPT model against [11] in Quetta and Peshawar.

Parameter	Quetta [11]	Our model results for Quetta	Deviation (%)	Peshawar [11]	Our model results for Peshawar	Deviation (%)
AEG (GWh)	209.80	214.03	+ 2.1	124.09	131.12	+ 5.66
Capacity Factor (%)	53.2 %	54.3	+ 2.06	31.5	33.3	+ 5.71
Cooling water requirements (m^3/year)	38,273	39,837	+ 4.8	32,241	34,158	+ 5.94
LCOE (¢/kWh)	11.43	10.78	- 5.68	19.06	17.38	- 8.81

4.2. WT Validation

The WT validation has been carried out against the pilot plant of 5 WT (2 MW each) which have been operating for two years in the same case study location [2]. Table 4 illustrates multiple years' performance besides the contractor's guarantee. The latter is only 3.1% deviated from this work's results while bigger deviations are found with the actual data and this is most probably because of the wind resource inter annual variation.

Table 4
The WT validation against the reported data in [2].

	Present work	Reported data for the 1st year	Reported data for the 2nd year	Contractor guarantee
AEG (Gwh)	34.1	39.6	36.9	35.2
Capacity Factor (%)	38.9	45.2	42.1	-
LCOE (¢/kWh)	4.3	-	-	-

4.3. SPT Optimization

The SPT parametric analysis has shown that the optimal TES-SM configuration is located at TES 16h and SM 3.2 as this configuration yielded the lowest LCOE of the SPT capacities from 50-100 MW. Thus, this configuration is taken as the base model for the SPT and then combined with different combinations of WT capacities ranging from 10-50 MW.

4.4. Model Performance

4.4.1. Standalone SPT Performance

The results show that a maximum reduction of -6.8% is observed in the AEG of the 100 MW SPT model when the aerosols scheme is adopted compared to the no aerosols scheme. This is projected at the LCOE as it is affected by an increase of 7%. In addition, lower deviation values are found in lower SPT capacities as a result of smaller solar fields' sizes, thus shorter slant ranges and less aerosols effect on the reflected irradiance.

4.4.2. Combined System Performance

The hybridization with WT has a major positive effect on the LCOE as expected, however, this is paired with a negative impact on the AEG. It has been found that as the WT capacity increases, the LCOE decreases, which is a result of lower investment costs of WT compared to SPT. In contrast, larger WT capacities result in lower AEG values when compared to a standalone SPT of a similar capacity. This is mainly due to the lack of a storage media for the WT. Table 5 illustrates the AEG and LCOE outputs for different combinations of SPT-WT over the range of 60-100 MW in both aerosols and no aerosols schemes.

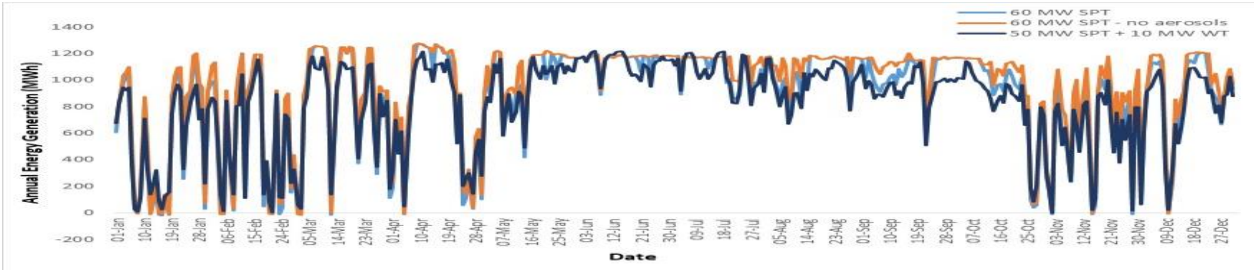
Combined SPT-WT outputs

Table 5
The evolution of the AEG and LCOE over different combinations of SPT-WT.

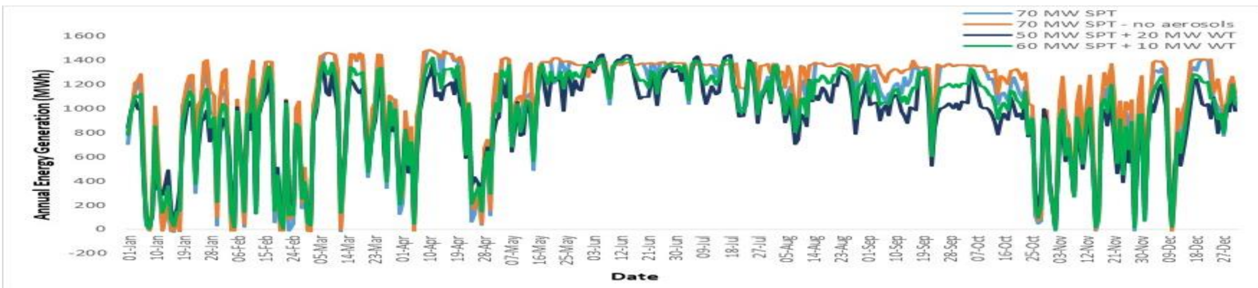
			WT									
			10 MW		20 MW		30 MW		40 MW		50 MW	
			AEG (GWh)	LCOE (¢/kWh)	AEG (GWh)	LCOE (¢/kWh)	AEG (GWh)	LCOE (¢/kWh)	AEG (GWh)	LCOE (¢/kWh)	AEG (GWh)	LCOE (¢/kWh)
SPT	50 MW	No aerosols	318.9	12.10	352.9	11.18	386.9	10.42	421	9.78	441.5	9.44
		Aerosols	302.7	12.8	336.9	11.77	370.9	10.92	405	10.21	425.5	9.84
	60 MW	No aerosols	376.7	12.21	410.7	11.41	444.8	10.73	478.9	10.15	-	
		Aerosols	356.7	12.96	390.7	12.05	424.8	11.29	458.9	10.64		
	70 MW	No aerosols	433.9	12.33	467.9	11.62	501.9	11	-		-	
		Aerosols	409.4	13.13	443.4	12.32	477.5	11.62				
	80 MW	No aerosols	490.2	12.39	524.2	11.75	-		-		-	
		Aerosols	460.9	13.26	494.9	12.52						
	90 MW	No aerosols	544.7	12.48	-		-		-		-	
		Aerosols	511.3	13.37								

Results in Table 5 show that the solar field and the TES capacity of the SPT is always considered as a dominant factor in the higher AEG contribution. On the other hand, the WT is proven to substantially decrease the LCOE, however, with no ability of compensating the energy loss caused by aerosols. Further, higher WT capacities do not possess the ability to match the AEG of a standalone SPT despite the latter being affected by aerosols.

In addition, the daily energy generation for different SPT-WT capacities has been evaluated. This is essential in order to examine the intra daily evolution of the AEG based on the higher/lower SPT and WT capacities. The results shown in Figure 2 illustrate that the hybridization has very limited benefits in this regards as the hybrid model can have higher energy generation values in only a few days over the year, especially from January until April (very obvious as the WT capacity becomes bigger). In addition, it can be seen that the higher share of WT, the lower is the overall AEG.



(a)



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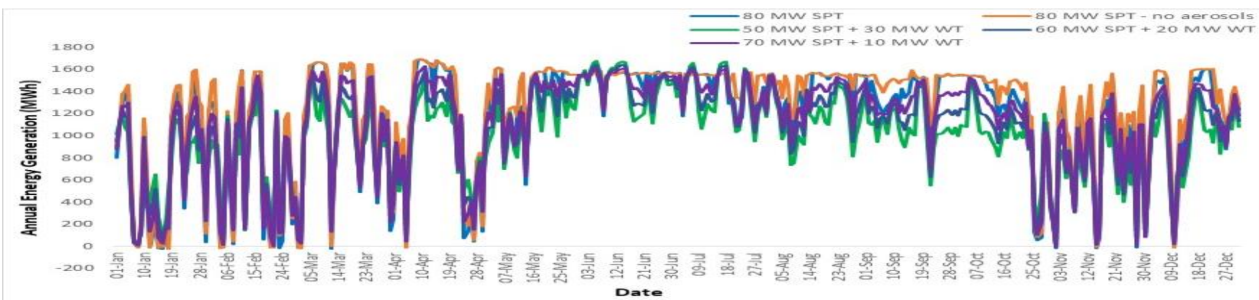

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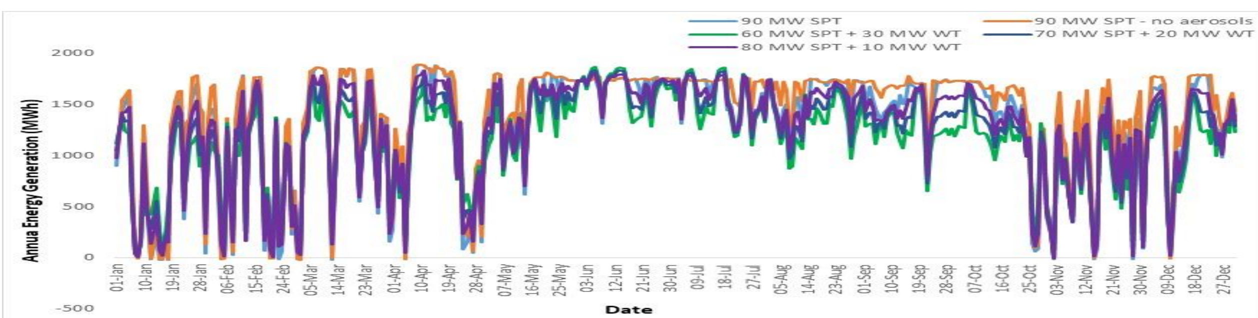

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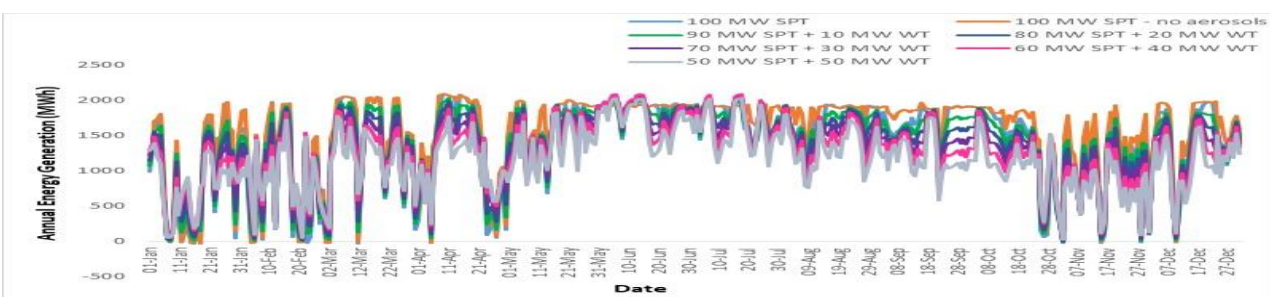

(e)

Fig. 2. The daily evolution of energy generation based on different combined SPT-WT capacities: (a) 60 MW, (b) 70 MW, (c) 80 MW, (d) 90 MW and (e) 100 MW.

In addition, the hybridization with WT is found to be limited in terms of the compensation of the energy losses due to the aerosols effect on the SPT. However, the hybridization offers a major decrease in the LCOE of the combined scenarios. This gives a preference criteria to the decision makers in the case where a slightly lower AEG is acceptable for much lower LCOE prices. This is clearly seen in Figure 3 which illustrates the evolution of the AEG in addition to the LCOE with different SPT-WT shares for a similar combined capacity, i.e. 100 MW.

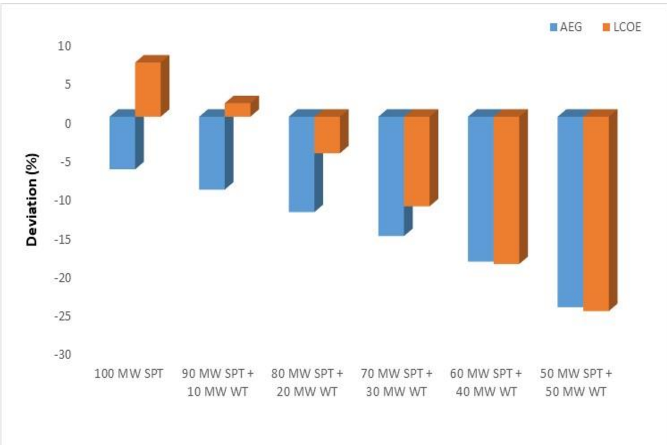

Fig. 3. Evolution of the AEG and LCOE for different SPT-WT combinations of 100 MW capacity.

The figure shows the differences in the AEG and the LCOE with a reference to the no aerosols 100 MW standalone SPT. Despite being the highest generating configuration, the aerosols impacted 100 SPT impedes a non-negligible increase of the LCOE, i.e. 7%. In contrast, the 50/50 configuration offers a great decrease of the LCOE (25.11%), however with a major decrease of the AEG of 24.62%. Intermediate results are found in the 80/20 and the 70/30 configurations as they contribute to a decrease in the LCOE by 4.72 and 11.57 %, respectively. This is impaired however with a penalty on the AEG as the latter decreases by 12.33 and 15.42%, respectively.

5. CONCLUSIONS

This work has evaluated the effect of aerosols on the solar field of the SPT technology in an arid region, i.e. Kuwait. Then, multiple WT hybridization scenarios have been simulated within the range of 60-100 MW. The results have shown that the greater the SPT capacity, the higher the aerosols effect on the energy generation and hence the LCOE. A maximum reduction of 6.8% of lower AEG has been observed on the standalone SPT of 100 MW compared to a no aerosols scenario. This contributed to an increase of the LCOE by 7%.

In addition, multiple trade-off scenarios have been found between the higher AEG and the lower LCOE when the integration of WT is realized. Both 80/20 and 70/30 combinations were found with intermediate results which might be appropriate for the decision makers as the decrease in the LCOE is higher than that of the AEG in both of these combinations.

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