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Design of Solar-Wind Hybrid Power System by using Solar-Wind Complementarity

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Abstract—**Environmental degradation is a rapidly growing concern across the globe, which is primarily caused by conventional fossil fuels-based power generation. This study examines the feasibility of generating electricity by using renewable energy sources (RESs) based hybrid power system (HPS). A general planning framework for integrating solar and wind energies in a HPS is proposed, that exploits the solar-wind complementarity to stabilize the combined power output. Specifically, it evaluates the solar-wind complementarity by using Pearson's correlation coefficient, and determines the optimal shares of solar-wind energies in power generation by minimizing the standard deviation of HPS power output. The proposed framework is evaluated on a case study in Pakistan, where sufficient solar-wind synergy potential exists. Our results show that values of solar- wind complementarity varies considerably from -0.351 (high complementarity) to 0.411 (low complementarity). It is observed that by using optimized shares, HPS power outputs exhibit less variations than the outputs generated by standalone solar or wind energy-based power systems. Best location for deployment of solar-wind HPS is identified as the one that maximizes the solar-wind complementarity benefits.**

Keywords-renewable energy sources; intermittency; solar-wind synergy; complementarity; hybrid power system; planning

I. INTRODUCTION

The gradual depletion and burning of finite resources of fossil fuels has contributed significantly in increased green-house gas (GHG) emissions and global warming [1]. In this context, integration of renewable energy sources (RESs) in the power sector is widely acknowledged as a cogent solution for curbing GHG emissions. RESs are clean, environmentally friendly, and naturally distributed sources of energy, which can be maintained locally [2]. As a result of spatial and temporal distributions of RESs, electricity can be generated in a distributed manner across several regions by harnessing local RES potential [3], [4].

Despite the numerous attractions of RES usage, their rapid adoption in power systems for electricity generation is hindered by the uncertainty in their availability. Due to the inherent intermittency of RESs, the power generation levels may fluctuate, causing an imbalance between the instantaneous power supply and demand [5], [6]. Failure to overcome this energy imbalance makes the power grid vulnerable to frequency deviations, voltage fluctuations at the interconnecting points, and power flow reversals [7], [8]. A popular method to increase the viability of the power system is to integrate two or more types of complementary RESs that serve as primary source of electricity generation [9], [10]. Two (or more) energy sources are said to be complementary in nature if their availability periods complement each other over time. Even though complementary RESs can be used to mitigate the RES intermittency, it requires some careful planning of the selection of deployment sites and the shares of RESs in the concerted power generation.

Various studies have been conducted on the RES complementarity with the objective of mitigating RES intermittency [10] – [15]. The authors in [10] discuss complementarity be- tween the outputs of RESs, and their proposed model utilizes the variable characteristics of power sources and the load. In [11] and [12], the authors combine solar-wind complementarity with hydropower to further stabilize the combined power produced. However, these studies exploit the flexibility of hydro-power units to mitigate the randomness in solar and wind RESs. The study in [13] investigates the key features of solar-wind complementarity in Britain for energy balancing. Similarly, the research conducted in [14] and [15] assesses the temporal solar-wind complementarity across Europe by means of correlation coefficients. One limitation of these studies is due to the dependence of their proposed models on either hydropower or some non-renewable energy source for addressing the intermittency of RESs. This dependence eliminates the possibility of quantifying the potential of RES complementarity as a sole contributor in achieving a reliable, sustainable energy supply. Additionally, due to the limitation of construction sites, the inclusion of large-scale hydropower units limits the possible deployment sites for solar and wind energies. Moreover, these studies do not provide any means of estimating the shares of RESs in the power generation, which is imperative in power system planning and operation.

This work analyzes the impact of capacity or share of RESs in the combined energy mix on the power generated, which in turn affects the amount of RES intermittency mitigated, energy storage requirements (if any), RES investment, and operational costs. Also, due to spatial distribution of RESs, the sizing requirements of RESs vary from location to location. Consequently, characterization of RES complementarity for power smoothing without optimizing the shares of RESs does not provide an adequate assessment. To address this shortcoming and the research gaps identified above, a planning framework is proposed that analyzes the solar-wind synergy and complementarity potentials across different regions to plan the deployment of a solar-wind hybrid power system (HPS). The outcomes of this work include the identification of the location that exhibits maximum solar-wind complementarity, and determines the optimal shares of solar and wind energies (RES Mix), which are made such that their combined power output possesses minimum variability. For this purpose, we use Pearson correlation coefficient to quantify the solar-wind complementarity, which helps in identifying the suitable site for HPS deployment. Then values of RES Mix at each site can be obtained by minimizing the standard deviation of the HPS output.

A case study for Pakistan is presented, which possesses a fairly large yet underutilized solar-wind synergy potential. Even though the country is rich in solar and wind energies, it still relies heavily on imported fossil fuels for power generation. During the span of 2017-2019, large coal power plants having a generation capacity of 3,300 MW were added to the energy mix, with over 8,000 MW planned for addition in the next five years [16]. The cause of massive dependence on fossil fuel-based power plants is the lack of experience with planning and operation of power system, that has a higher share of intermittent RESs in the overall energy mix. To the best of authors' knowledge, a feasibility study on solar-wind complementarity potential in this region has not been explored before. Our analysis shows that intermittency of the power generated by solar-wind HPS can be mitigated by exploiting solar-wind complementary characteristics and by optimizing RES Mix. Further, by exploiting the proposed model, the addition of new coal power plants in the country could be avoided.

The rest of the paper is organized as follows. Section II describes the system model and provides an insight to the problem formulation. Section III presents the case study, with a focus on the energy situation in Pakistan. The results and some policy recommendations are presented in Section IV and the paper is concluded in Section V.

II. SYSTEM MODEL

The generalized version of the proposed framework is shown in Fig. 1. As this work deals with the planning of solar-wind energies based HPS, identification of deployment site (location) and determination of RES Mix are identified as planning parameters for the deployment of HPS. For this purpose, different sites are analyzed and the final selection for location is made based on the solar-wind complementarity assessment. There are three steps in which the problem of planning for solar-wind energy based HPS can be approached. The first step involves the computation of capacity factors, while the second and third steps deal with resource complementarity analysis and resource variability evaluation, respectively.

In the first step, capacity factors (CFs) of solar photovoltaic (PV) unit and wind turbine are computed by using data of solar irradiation and wind speeds at all locations. Then these values are made input to the resource complementarity analysis, where solar and wind energy characteristics are used to determine the extent to which these resources complement each other in a given region. This quantification task is achieved through the computation of correlation coefficient across all sites. The estimates of location along with solar-wind capacity factors are then fed to the variability assessment block, where standard deviation of HPS power output is computed. This block is also responsible for the determination of optimized RES Mix. The following subsections describe the processes that occur inside each block.

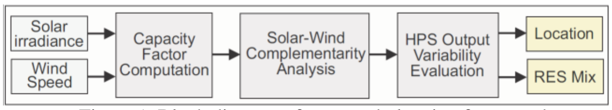

Figure 1. Block diagram of proposed planning framework.

A. Capacity Factor Computation

The capacity factor of a power generation plant is a measure of the energy generated during some period of time as compared to its maximum output. Let $E_s^n(t)$ and $E_w^n(t)$ denote the CFs of solar PV unit and wind turbine, respectively, at location n and time t.

The CF of solar PV unit is determined as follows,

$$E_s^n(t) = \frac{P_s^n(t)}{P_{stc}} \tag{1}$$

where $P_s^n(t)$ is the power generated by solar PV unit at location n and time t, and P_{stc} refers to the power generated by PV unit under standard conditions of 1000 W/m^2 solar irradiance and 25^{0}C temperature. The actual power generated by a PV unit at location n and time t is modeled as [17],

$$P_s^n(t) = \eta_s A G^n(t) \tag{2}$$

where η_s is the conversion efficiency, A is the area of the PV panel and $G^n(t)$ is the irradiance at location n and time t. Similarly, the CF for wind turbine at location n and time t is computed as,

$$E_w^n(t) = \frac{P_w^n(t)}{P_{wr}} \tag{3}$$

where $P_w^n(t)$ is the power generated by wind turbine at location n and time t, and P_{wr} is the rated power of wind turbine. As the available data contains information about wind speeds, we can express $P_w^n(t)$ as,

$$P_w^n(t) = \begin{cases} P_{wr}\frac{(v^n(t)-v_c)}{(v_r-v_c)} & v_c \le v^n(t) \le v_r \\ P_{wr} & v_r \le v^n(t) \le v_{co} \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

where v_c is the cut-in speed at which the turbine starts generating power, P_{wr} is produced at the rated speed denoted by v_r, $v^n(t)$ is the wind speed at location n and time t, and v_{co} is the cut-off speed after which the turbine is shut down for safety purposes. This work assumes that similar types of wind turbines are considered for installation at all locations, which is why the rated power of turbines at all locations are the same.

Let $P_h^n(t)$ denote the power output of solar-wind energies based HPS at location n and time t. Assuming both solar PV units and wind turbines are installed at location n, HPS power output can be expressed as,

$$P_h^n(t) = \alpha^n P_s^n(t) + (1 - \alpha^n) P_w^n(t) \tag{5}$$

where α^n represents RES Mix that is, the shares of solar and wind energies in power output of HPS at location n. Note that α^n is the design variable and it is not dependent on time. RES Mix takes the values in the range [0,1]. When α^n is 0, it means that only wind turbines are installed and when α^n is 1, only solar PV units are installed at location n. Any other value ($0 < \alpha^n < 1$) indicates RES mix consisting of some solar PV units and wind turbines.

B. Solar-Wind Complementarity Analysis

In this study, Pearson correlation coefficient is computed, which is the most popular statistical measure that evaluates the relationship between any two random variables. The degree of relationship (or complementarity value) is defined by values in the range given by [-1, 1]. The correlation coefficient takes the value of zero when there is no relationship between the assessed RESs. A positive value is indicative of the lack of complementarity, i.e. all assessed RES(s) exhibit the same spatial and temporal characteristics during the period of observation.

To assess the degree of complementarity, the convention is to first determine the combined potential of RESs by using their individual CFs that have been averaged over time. Let γ^n denote the solar-wind complementarity value at location n. The value of γ^n is computed as follows.

$$\gamma^n(t) = \frac{\sigma_{s,w}^n(t)}{\sigma_w^n(t)\sigma_s^n(t)} \tag{6}$$

where $\sigma_{s,w}{}^n(t)$ is the covariance of solar and wind energies at location n and time t, and $\sigma_s{}^n(t)$ and $\sigma_w{}^n(t)$ represent the standard deviations of the energies produced by PV units and wind turbines at location n and time t, respectively. These values are computed by using hourly values of solar and wind CFs that are determined for a certain time period, τ. The variance and covariance up till time τ are determined as,

$$(\sigma_s^n)^2(t) = \sum_{m=1}^{\tau} [E_s^n(m) - \mu_s^n]^2 \tag{7}$$

$$(\sigma_w^n)^2(t) = \sum_{m=1}^{\tau} [E_w^n(m) - \mu_w^n]^2 \tag{8}$$

$$\sigma_{s,w}^n(t) = \sum_{m=1}^{\tau} [E_s^n(m) - \mu_s^n][E_w^n(m) - \mu_w^n] \tag{9}$$

where $\mu_s{}^n$ and $\mu_w{}^n$ represent the average values of solar and wind CFs, respectively, at location n. $E_s{}^n(m)$ and $E_w{}^n(m)$ represent the solar and wind CFs, respectively, at location n and time m. In this study, the span of a year is selected i.e. variance and covariance values are computed for 365 days using hourly averages.

C. Variability Evaluation

The power generated by solar-wind based HPS is prone to variations due to the randomness of the availability of solar and wind energies. On the annual scale, the summer months (May, June, July) experience a greater number of peak sunlight hours than those in winter months (November, December, January). The seasonal dependence along with the duration of peak sunlight hours renders the PV power generation profiles to be inconsistent and intermittent in nature. Similarly, the output of wind power generation is also intermittent as it is greatly influenced by the speed and direction of wind.

The objective of this work is to identify optimal RES Mix that minimizes the variation in the power output of HPS around its mean value. For this reason, we develop the following mathematical formulation to identify the RES Mix such that the standard deviation of the HPS power output, which is denoted by $\sigma_h{}^n(t)$, is minimized.

$$\min_{\alpha^n} \sum_{t=1}^{T} \sigma_h^n(t) \tag{10}$$

$$\text{s.t.} \quad 0 \le \alpha^n \le 1 \tag{11}$$

$$n \in \{1, \ldots, N\} \tag{12}$$

$$t \in \{1, \ldots, T\} \tag{13}$$

where N represents the total number of locations and T is the total time period. To solve this, a simple algorithm is developed that is implemented in MATLAB. Algorithm I illustrates how RES Mix is determined. After setting the parameters τ, T, N, $\Delta\alpha$, $E_s{}^n(t)$ and $E_s{}^n(t)$, the solar-wind complementarity value for each location is determined by using (6). The best location for HPS deployment is identified as the one that exhibits the most negative complementarity value. Then RES Mix is computed. For the best location n_{best}, we compute standard deviation of the power output of HPS. Then α at that location is varied with the step size $\Delta\alpha$ and the corresponding standard deviation is determined. The optimized RES Mix is identified as the one that minimizes the standard deviation of the HPS power output.

III. Case Study

To evaluate the proposed framework, we assess the solar-wind synergy and complementarity potential across twelve different locations of Pakistan as highlighted by location indexes from A to L in Fig. 2. Different parameters that are used for simulation in this study include solar irradiance under standard conditions of 1.0 kW/m2, unity solar PV panel efficiency, $\Delta\alpha$ of 0.01 and cut-in, rated, and cut-out wind speeds of 3 m/s, 15 m/s, and 25 m/s respectively [6].

Algorithm 1: Determining location and RES Mix.

```
Initialize τ, T, N, Δα, E_s^n(t), E_w^n(t).
for n = 1 : N do
    Determine σ_{s,w}^n, σ_s^n, σ_w^n and γ^n.
    Identify best location that gives γ_min,
                                   γ_min = min_n γ_n
end for
for α = 0 : Δα : 1 do
    Compute P_h^n for(t) and σ_h^n.
    Determine optimized RES Mix that gives σ_min,
                                   σ_min = min_α σ_h^n
end for
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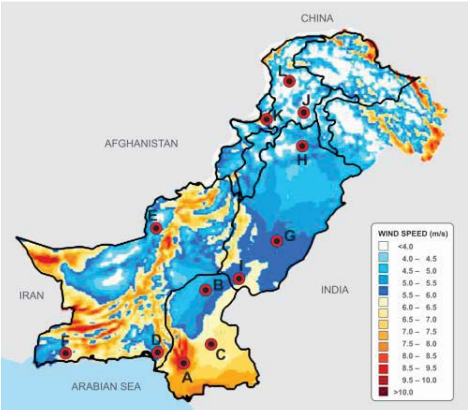

Figure 2. The red circles denote the selected locations.

A. *Dataset*

The data for solar irradiation and wind speeds for these regions are acquired from European Center for Medium-Range Weather Forecasts (ECMWF) ERA5 dataset [19]. For this study, solar and wind CFs are determined for the year 2018, at the time resolution of an hour. ERA5 is known to have an inherent spatial resolution of 0.28125 degrees, which are equivalent to 31 km. As it is interpolated to a 0.25/0.25 grid, having 1440 equally spaced grid points at a spatial resolution of 0.25 degrees, appropriate approximations are made to the geographical coordinates of the selected regions of Pakistan.

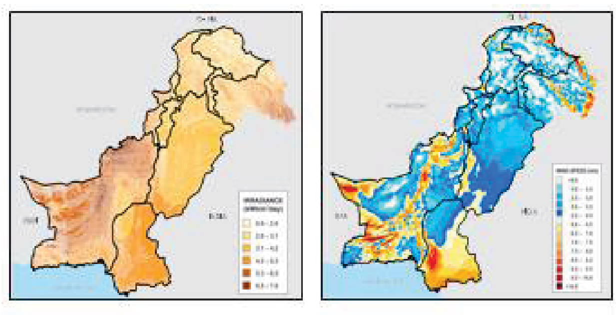

Figure 3: (a) Solar potential, (b) Wind potential across Pakistan.

B. *Solar-Wind Synergy Potential*

The geographical location of Pakistan makes it an ideal candidate for the recipient of solar irradiance throughout the year. With an annual average solar irradiation of 5.5 kWh/m^2 and daily 6-8 peak sunlight hours, the country can harness the freely available solar resource to meet its daily energy requirements at a negligible cost [20]. Fig. 3(a) shows the solar irradiance across the country. This map has been generated with the help of renewable energy data explorer, which is an online geo-spatial tool developed by National Renewable Energy Laboratory (NREL) [21]. The data required to draw this map is also obtained from NREL. In contrast to the northern belt of the country that receive direct normal irradiance anywhere from 1.0 to 3.0 kWh/m^2 per day, the southern regions are more abundant in solar resource.

In addition, the country is known to have 346 GW potential of wind energy, as is indicated by NREL [22]. To visualize the spread of wind speeds across the country, consider Fig. 3(b). Relative to coastal areas, where wind speeds have a fair magnitude of 5-10 m/s, the rest of the country registers wind speeds below 6 m/s.

IV. Results and Discussion

This section presents the results of solar-wind complementarity assessment and RES Mix determination across different regions of Pakistan for the deployment of HPS.

A. *Solar and Wind Capacity Factors*

Table I displays the hourly average values of solar and wind CFs for each of the location. Due to the absence of solar energy at night, the average hourly values for solar energy are not good indicators of its actual potential. However, these results have been reproduced here just for the sake of comparison. To obtain these values, the hourly resource potential for the whole year is averaged over time (hours). Notice that solar energy remains relatively consistent across all regions of the country. In contrast, the wind CF varies considerably. Comparing the hourly average strengths of both solar and wind energies, it is apparent that areas of Sindh have more abundance of wind resource than any other region of the country.

TABLE I: Hourly Capacity Factors and Complementarity Values for Different Regions

Province	Location		Solar CF	Wind CF	Complementarity Value
	Index	Name			
Sindh	A	Jhimpir	0.237	0.658	-0.137
	B	Sukkhur	0.237	0.263	-0.351
	C	Hyderabad	0.241	0.596	-0.198
Balochistan	D	Hub	0.236	0.499	0.035
	E	Quetta	0.242	0.118	0.411
	F	Gawader	0.246	0.349	0.112
Punjab	G	Bahawalpur	0.237	0.282	-0.250
	H	Chakri	0.217	0.163	-0.188
	I	Sadiqabad	0.237	0.346	-0.309
KPK	J	Haripur	0.215	0.047	-0.037
	K	Peshawar	0.212	0.048	0.031
	L	Besham	0.203	0.061	-0.155

B. *Solar-Wind Complementarity Across Pakistan*

Table I also shows the solar-wind complementarity values for all regions. Notice that even though the CFs for both solar and wind energies in the regions of Sindh have a higher percentage than those of Punjab, the complementarity value of Punjab regions turn out to be more negative. The reason is that the complementarity value does not indicate the relative strengths of the solar and wind energies in any given region. Among all the examined regions, Sukkhur exhibits the highest amount of solar-wind complementarity. Quetta has the most positive value of correlation coefficient, which means that it exhibits the lowest level of solar-wind complementarity.

All locations (D-F) of Balochistan has the positive complementarity value, indicating that it would not be advisable to adopt solar-wind hybrid power plants in this province. In contrast, KPK has a mixed range of complementarity values. Peshawar has the least solar-wind complementarity potential in KPK, while Besham has a negative complementarity value.

C. Determination of RES Mix

The standard deviation of the power output of HPS is plotted against RES Mix in Fig. 4 for all locations. In this work, the optimal value of α^n is denoted by α^n_{opt}. The variations in HPS power output gets reduced and reaches a minimum value when $\alpha^n = \alpha^n_{opt}$. For $\alpha^n = 0$ (wind only) and $\alpha^n = 1$ (solar only) cases, the variations in HPS power output are equal to the variations in wind and solar energies respectively. For $0 < \alpha^n < 1$, the variations in HPS power output are due to the combination of both solar and wind energies. For instance, the optimized RES Mix at location A (Jhimpir) turns out to be 0.24 (that is, solar energy has a share of 24% and wind energy has a share of 76%) and the standard deviation of power output is at its minimum value of 0.56. This combination is expected because (a) variation of wind energy around its mean value is lower than that of solar energy as can be seen from y-intercept of blue curve in Fig. 4, and (b) there is a fairly large potential of wind resource to generate power (roughly 66\%) as can be seen from Table I. Similar inferences can be drawn for other locations. The values of optimized RES Mix obtained at each location are tabulated in Table II.

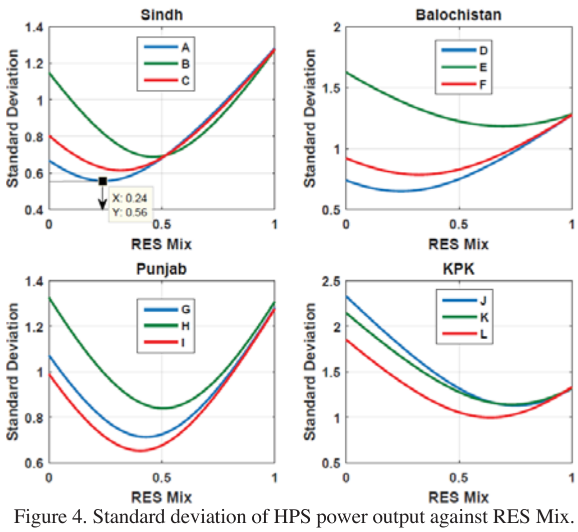

Figure 4. Standard deviation of HPS power output against RES Mix.

Fig. 5 displays the curves for capacity factor of the output of HPS for solar only case ($\alpha^n = 1$), wind only case ($\alpha^n = 0$), and an optimal combination of solar-wind energies ($\alpha^n = \alpha^n_{opt}$) for two locations with high solar-wind complementarity (Location B) and low solar-wind complementarity (Location F). It can be seen that even though Location F has a positive value of correlation coefficient, it still exhibits some degree of solar-wind complementarity for the optimized RES Mix during winters. It can be concluded from this observation that by optimizing RES Mix, the intermittency of solar-wind energies can be minimized even at locations that have low complementarity values.

TABLE II: OPTIMIZED RES MIX FOR DIFFERENT REGIONS

Province	Location		RES Mix
	Index	Name	
Sindh	A	Jhimpir	0.24
	B	Sukkhur	0.46
	C	Hyderabad	0.32
Balochistan	D	Hub	0.24
	E	Quetta	0.69
	F	Gawader	0.32
Punjab	G	Bahawalpur	0.43
	H	Chakri	0.51
	I	Sadiqabad	0.40
KPK	J	Haripur	0.75
	K	Peshawar	0.73
	L	Besham	0.64

D. Inferences and Policy Recommendations

The solar-wind complementarity analysis presented above can be used to plan the deployment of solar-wind hybrid power systems. The following recommendations are made to avoid the capacity addition of coal-based power plants, and to harness the freely available, clean energy for the generation of electricity. From the analysis presented in this study, it can be deduced that interior and coastal regions of Sindh make an excellent choice for the integration of solar and wind energies. Also, there are already 22 wind independent power plants (IPPs) installed in Jhimpir. With the negative complementarity value (-0.137), solar PV plants could be installed in Jhimpir to exploit solar-wind complementarity. This addition of solar power plants to already existing wind power plants could effectively improve the power system reliability. Any excess power generation could be used to meet the energy requirements of neighboring communities. Additionally, for withdrawing maximum benefits from both resources, it is recommended to make use of solar-wind variability assessment. In this context, Table II provides some useful information for combining each resource.

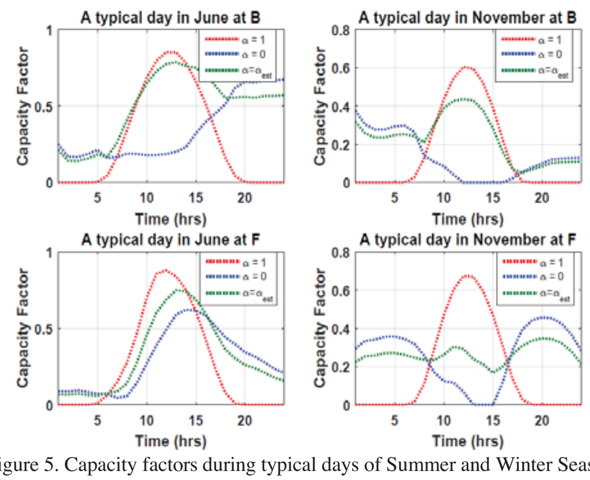

Figure 5. Capacity factors during typical days of Summer and Winter Season at Location B (Sukkhur) and Location F (Gawader).

V. Conclusions

In this paper, an evaluation of the solar-wind synergy and complementarity potentials was presented for determining the set of best locations and initial values of RES mix. For this purpose, a framework for planning the deployment of solar-wind hybrid power system was proposed. An algorithm based on solar-wind complementarity assessment and standard deviation of hybrid power system output was developed that helped in identifying the set of best locations to maximize the utility of complementary solar-wind energies. It also allows the determination of optimized RES mix by minimizing the variation in the power output. From the analysis presented, it can be observed that by optimizing RES Mix, the intermittency of solar-wind energies can be minimized even at locations that have low complementarity values.

VI. Acknowledgment

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