Optimizing Wind-Solar Power Plants: Novel Structures for Identifying Potential Sites and Capacity Ratios in Iran

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This paper proposes two novel structures to identify potential sites for wind-solar power plant construction, along with the optimal capacity ratio of wind-to-solar power plants in each region. The first structure comprises three modules, namely, identifying the best wind turbine and its output power, predicting global tilted irradiation at the optimal angle, and obtaining the capacity ratio of wind-to-solar power plants. The second structure is used to identify regions with the highest energy harvesting potential per square meter by evaluating the algebraic sum of two Capacity Factors (CFs) and determining the capacity ratio based on the maximum installed capacity of each power plant in that area. The results of applying these structures to 4900 points in Iran show that the solar power plant CF is higher than 20% in more than 95% of the selected points, while the CF for wind power plants was only above this threshold in 12% of the examined points. The selection of the optimal wind turbine significantly affects the CF and output power, and hybridization of the two power plants has little effect on improving the CF. Additionally, less than 10% of the areas were deemed suitable for constructing hybrid power plants, according to the second model. This study provides valuable insights into identifying potential areas for wind-solar power plant construction and determining the optimal capacity ratio of wind-to-solar power plants. The proposed structures can assist policymakers and industry experts in making decisions about where to build wind-solar power plants, helping to increase the efficiency of renewable energy generation.

keywords: *Capacity factor, Optimum ratio of wind turbine capacity to solar power plant capacity, Renewable energies, Solar power plant, Wind power plant.*

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NOMENCLATURE

i	Region
j	Turbine
t	Time
α	Latitude
β	Longitude
θ	The panel angle relative to the horizontal plane
γ	Albedo
CF	Capacity factor
x	Optimum number
$Lifetime$	Lifetime
P	Output power
v	Wind speed
$EGTI$	The amount of radiation incident on the surface of the angled panel
y_i	The angle of installation of a panel in the ith choosing
α_i	The optimum ratio
$Pmaximum_i$	The practical capacity of the power plant in region
$P_{WT,i,t}$	The normalized value of the output power of wind turbine power plant in region i at time t
$P_{PV,i,t}$	The normalized value of the output power of a photovoltaic power plant in region i at time t
β_i	The real ratio of two power plants
$MILP$	The mixed-integer linear optimization

1. INTRODUCTION

About 80% of the energy demand is provided by fossil fuels [1]. Burning fossil fuels releases carbon dioxide, which is the primary cause of global warming, and contributes to air, water, and soil pollution [2, 3]. Climate change will lead to various alterations on Earth, including an overall rise in temperature, altered precipitation patterns, and an increase in occurrences of droughts and storms [4]. To deal with such effects, it is necessary to change primary energy supply sources from fossil fuels to renewable energies [5, 6]. It is also predicted that the demand for electric energy will be more than 38,000 terawatt-hours per year by 2050 [7]. Such demand must be met with no or low-carbon technologies. This increase in energy demand and the destructive environmental effects of fossil fuels are driving forces to move towards sustainable and green energy sources [8]. Many countries have made it a priority to achieve a stable, low-carbon, and environmentally sustainable economy by transitioning to renewable energy sources to prevent further climate change [9].

Currently, the share of developing countries in the emission of greenhouse gases is growing rapidly [10]. As a result, many of these countries have turned to the use of renewable energies [11, 12]. Renewable energy sources, such as solar, wind, water, biomass, and geothermal energy, are gaining increasing attention as competitive alternatives to fossil fuels. Among these sources, solar and wind energy are particularly noteworthy [13, 14]. Significant advancements in technology and cost reduction have led to the production of solar panels and wind turbines with higher capacity and efficiency, making these two energy sources increasingly important [15–17]. Over the decade spanning from 2010 to 2020, the cost of power generation through photovoltaic panels has significantly decreased, with the equalized cost at the power plant level dropping by 85% [18]. Both of these energy sources can satisfy the grid's demand, either by directly supplying power to the grid or operating independently of it [19]. Also, these two sources of energy can be combined or other sources to make the most use of renewable energies [20]. Meeting the goal of limiting global temperature rise to 1.5 degrees Celsius, as outlined in the Paris Agreement, requires solar panel capacity to reach 5200 GW by 2030. This represents a seven-fold increase over the 2020 installed capacity [18]. The World Wind Energy Association (WWEC) has predicted that 335 gigawatts of wind turbine power plant capacity will be installed in the world between 2020 and 2024 [21]. During the last two decades, the installed wind turbine capacity has increased by 14% annually and provides about 6-7% of electricity [22]. Also, both wind energy and solar energy have much fewer environmental effects due to low emissions during their life cycle [23]. The use of solar and wind energy in the last three decades in China and America has reduced the emission of carbon dioxide in these countries [24]. Life cycle analysis has shown that using wind energy to meet 22% of Europe's electricity demand throughout its entire life cycle results in direct emissions of only 4-14% compared to equivalent fossil fuel power plants [25]. Solar energy in Iran has great potential. Iran has a clear sky for about 300 days a year and has many available lands for installing solar energy [26]. The central and southern regions of Iran are the most suitable places for solar panels, and regions such as Delgan, Mahshahr, Shushtar, Abadeh, and Fadeshk have a radiation of more than 500 watts per square meter [27]. 1.2 million hectares of Iran have an average wind speed of more than 8 m/s [28]. Although many regions in Iran have the potential to install wind turbines, only 300 MW of wind turbines have been installed throughout the country [6, 29]. Iran, like other countries, can benefit from using wind and solar energy to reduce greenhouse gas emissions. A combination of a wind turbine, solar panel, diesel generator, and battery system in Iran has the potential to reduce up to 2000 kg of carbon dioxide emissions per household [6]. Replacing natural gas with wind and solar energy to meet heating demands in Iranian buildings has the potential to reduce carbon dioxide emissions by three percent per 10 terawatt-hours per year [30].

Haddad et al. [31] combined renewable energies for different purposes. One of the reasons is the stability of the energy produced because the main source of energy production in them depends on random natural phenomena. Also, additional systems for energy storage are needed next to them. The concept of a green-green energy system consisting of solar, wind, and fuel cell energies has been determined and its application has been investigated in Lebanon. Huang et al. [32] used the flexibility of hydropower energy against the uncertainty of solar and wind energy to increase the optimum use of resources. But there are risks including lack of output, power cuts, and wasted water in front of such a system. As a result, three risk indicators were used to quantify them, which were used in the objective function, and then a two-layer nested optimization approach was used. The results of the model for this system in China indicated that the probability of power outages will be reduced to zero and water wastage will be reduced between 47 and 74 percent. Jahangir et al. [33] combined Wave energy with solar and wind energies and batteries and forms a system independent of the grid to show that it can meet the demand of three thousand households in three coastal regions of Iran. Li et al. [34] determined the best combination of a photovoltaic panel, wind turbine, and biomass for the rural areas of western China with the combined optimization model for renewable electric energy. The results showed that this system includes 104 kW panels, three 10 kW wind turbines, and 50 kW biomass. 331 kWh battery will be better from the economic and environmental point of view than the network developed. Sun and Harrison [35] used an optimization model to show that the combination of solar and wind energy will make the output energy uniform and maximize the capacity of using renewable energy in the grid. Zhang et al. [36] developed the possible optimum operation model to reduce the existing uncertainties of the combined wind-solar-water system. Yan and Jianwei [37] estimated the probability density function of their model's state variables and derived the model's operation rules as the two keys for solving their model, which improved the system by about 15%. They stated that the backpropagation neural network algorithm can instantly detect the faults in the combined solar-wind system. The three-degree-of-freedom PID controller for active power management control of the combined solar and wind system can improve management by 329% in Sahu et al.'s model [38].

Mehrjerdi et al. [39] developed a model to meet the demand of a building, charge electric and hydrogen vehicles and reduce related pollution, which is a combination of solar, wind, and storage energy. This model uses integer linear optimization for cost minimization, and the optimum cost mode is about 3000 dollars per year. Jahangir and Cheraghi [40] developed a model and concluded that the combined system including a 150-kW biogas generator, 81 kW photovoltaic panel, wind turbine, and storage system obtained by their model using HOMER software was the best economic combination for use in rural areas of Fars province [40]. Wang et al. [41] evaluated the best combination of solar-wind-hydro energy on a global scale for 3080 regions and the total potential installed capacity was 1699 GW, the largest share of which can be in the Asia and Pacific region with 40%. Jamshidi et al. [42] developed a model to eliminate the need for accurate and long-term data to evaluate hybrid systems. Xie et al. [43] investigated an approach of regression models for a system consisting of wind-photovoltaic-battery-diesel in Iran and its results showed that the more the set of training data, the higher the accuracy. It is possible to check the combination of solar and wind energies with storage hydroelectricity to minimize the waste of the three desired energies and maximize the storage in the wind power plant employing the integer hybrid linear optimization model. Dhunny et al. [44] obtained the most suitable place for the construction of a wind-solar power plant on the island of Mauritius by the fuzzy logic model in. Ulah et al. [45] in research about the techno-economic analysis feasibility of hybrid offshore wind-solar PV power plants stated that phase limitations were wind and solar power, site height, residential areas, and proximity to the network. The two sites with the highest potential had a production capacity of 162 and 281 GWh. Combinations of solar, wind, water, and biomass systems were investigated in rural areas of Pakistan. First, 12 combinations connected and independent of the network were evaluated by an optimization model that evaluated five criteria related to economy, reliability, ecology, society, and topography, and then the combination decision model selected the best combination. Ara et al. [46] showed that solar-biomass-hydroelectricity-battery is the best combination with a life cycle cost of about 11 million dollars using a model that includes fuzzy logic, multi-objective optimization, and evaluation based on the distance of solution methods. The particle swarm optimization model determines the best layout of offshore wind-photovoltaic power plants, and in the second layer, an economic analysis is performed to check the applicability of each mode. Ganjei et al. [47] by using HOMER software, showed that a combination of solar energy, wind, and diesel generators together with a battery can meet the energy demand of 22-kilowatt hours per day for a village in East Azerbaijan province. Jahangiri et al. [48] showed that the lowest and highest percentage of use in these areas is Darab with 87% and Jask with 100% by a survey of 103 points in Iran to meet the demand of the building sector by using a combination of solar and wind energy. Erken et al. [49] designed and optimized a solar-wind charging station with HOMER software as they found out that the increase in the use of electric vehicles brings challenges in terms of providing electricity through sustainable technologies, electric load management, and creating new charging stations. Peng et al. [50] Optimized a hybrid system for solar-wind-based water desalination by reverse osmosis. They stated that the best combination includes 44% wind energy and 56% solar energy with a cost of 0.064 dollars per kilowatt hour. It was shown that a combination of optimization models to evaluate a system consisting of a wind turbine, photovoltaic panel, and battery for the production of freshwater from the reverse osmosis process in Iran will provide the best results and reviews. Hoseinzadeh et al. [51] found that river systems have problems producing electrical energy due to a lack of water in dry and hot seasons. For this purpose, they used solar and wind systems along with river systems. The best combination in Mashhad includes 61 kilowatts of hydroelectricity, 20 kilowatts of solar power, and 7.5 kilowatts of wind with an initial capital of 231 thousand dollars. Al-Shereiqi et al. [52] managed the fluctuations of a combined photovoltaic panel and wind turbine system with a heuristic optimization with a numerical iterative algorithm. Rezaei et al. [53] obtained the most suitable combination for a four-square-kilometer of land with a system including 39 megawatts of wind turbine and 3.5 megawatts of panels. 14 criteria and a fuzzy multi-criteria optimization model were considered to find the best place to build a solar-wind hybrid system that can produce hydrogen, and it was determined that Yazd will be the best place. In the research done by Lopez et al. [54] the power smoothing index showed that the combination of offshore floating systems of wind turbines and photovoltaic panels has a smooth output power with 63% of Spain's rejection. Thakre et al. [55] stated that even bladeless wind turbines can be combined with solar panels. Rakhshani et al. [56] considered multiple different wind turbine technologies installation for hybridizing wind-diesel-battery system planning. They stated that, unlike the other models that considered the wind turbine as a general model, a new approach in the combination of a wind turbine, diesel, and battery includes the type of turbine as a decision variable. Mehrjerdi [57] used the mixed-integer linear optimization method (MILP) and its results showed a five percent reduction in planning costs. A linear optimization model obtains the best turbine in a system consisting of a wind turbine and a photovoltaic panel.

Although numerous studies have been conducted on renewable energy-based power plants and their hybridization, limited research has been focused on establishing a comprehensive model for identifying suitable locations for hybrid power plant construction and determining the optimal capacity ratio of two power plants. This study aims to fill this gap by introducing two models that can identify suitable locations and determine the appropriate capacity ratio for two power plants. Also, This article aims to provide a solution to determine the optimal capacity of two energy conversion technologies without controlling the input so that the output of the hybrid power plant becomes more uniform. The uniformity of the production level can lead to an increase in the penetration rate of renewable power plants.

2. METHODOLOGY

In this section, two models are introduced to identify potential areas for the construction of hybrid power plants and the optimum capacity ratio of the two power plants. The first model identifies areas for the construction of a hybrid power plant to increase the capacity of the power plant to provide the base load (or improve the capacity factor) and the second model identifies the areas with the maximum energy that can be harvested per square meter of land allocated to the power plant.

Uncertainty in predicting the intensity of solar radiation and especially wind speed affects the output power of energy conversion technologies, also this issue can ultimately affect the optimal capacity ratio of two power plants, but in this study, the uncertainty in predicting wind speed and the intensity of the sun's radiation has not been checked

A. Improving the capacity factor

This section introduces a model to find the optimum ratio of two power plants based on renewable energies with the approach of the obtained maximum share in providing the base load, in other words, the optimum value of the ratio of the capacity of two power plants brings the maximum capacity factor. The two power plants investigated in this study are wind power plants and photovoltaic panels, and in this study, the capacity factor of the hybrid power plant is calculated based on the maximum production of the hybrid power plant in that area. According to the change in wind speed and solar radiation during the day and night, it is possible to improve the capacity factor of the hybrid power plant. Determining the ratio of two power plants to obtain the maximum defined capacity factor is obtained through a model consisting of three modules. These three modules are named wind turbine, solar power plant, and the ratio of two capacities of the power plant. Using the wind turbine module, the best wind turbine in each region is identified, and based on that, the production of that power plant is predicted every hour. Studies show that choosing the optimum wind turbine has a significant impact on the capacity factor of the power plant [58]. The solar power plant module calculates the optimum time intervals for a structure with the possibility of installing a photovoltaic panel on n angles along with the angle. The optimum ratio module, with the help of a mathematical programming model, determines the optimum ratio of two power plants in such a way that the maximum capacity factor of the hybrid power plant is determined. To calculate the capacity factor, the capacity of the power plant is needed, and here this capacity is defined as the maximum that is obtained based on the conditions of the region (it differs from the common definition) in practice it will be smaller or equal to the total capacity of two power plants. Fig. 1 shows the conceptual model proposed in this research.

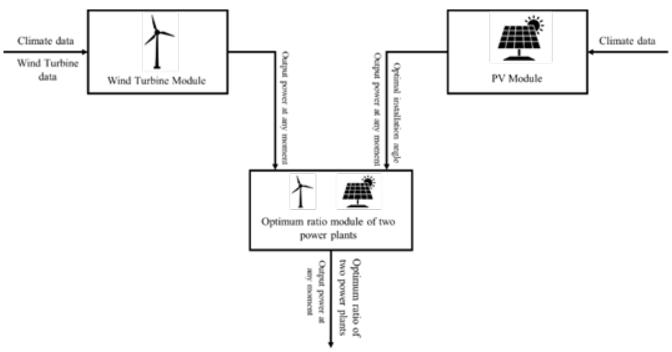

Fig. 1. Conceptual model of choosing the optimum ratio of solar and wind power plants in a region

A.1. Wind turbine module

Climate change can impact the performance of wind turbines in a particular region, and variations between turbines can cause their performance to differ, even if they have the same capacity and are in the same area. To ensure optimal energy production, it is crucial to select the most suitable wind turbine for the prevailing environmental conditions. This study proposes using a wind speed-output power diagram to determine the wind turbine's output power at any given time based on environmental factors and the wind turbine itself. To assess the optimal selection of wind turbines, two criteria are considered: maximum capacity factor and maximum profit. The optimal wind turbine selection is determined based on achieving the highest capacity factor. The optimization problem is formulated as a Boolean linear problem, with decision-making variables equal to the number of available wind turbines. These variables can either be zero, indicating no selection, or one, indicating the selection of a wind turbine. The proposed optimization problem for selecting the optimal wind turbine in each region is expressed as Eq. 1.

$$Max\ Z_i = \sum_{j=1}^{n} CF_{j,i}\, x_{ij} \tag{1}$$

s.t.

$$\sum_{j=1}^{n} x_{i,j} = 1, \qquad x_{i,j} : 0\ or\ 1$$

In Eq. Eq. (1), $CF_{j,i}$ is the capacity factor of turbine j in region i, n is the number of available turbines and the problem clause indicates the number of wind turbine choices. $x_{i,j}$ indicates the optimum number of selected turbines in that area. The wind turbine capacity factor can be calculated based on the environmental conditions and wind turbine specifications based on the wind turbine catalog. In a simple case, based on the information stated in the wind turbine catalog, the output power of the wind turbine can be calculated based on the wind speed. The capacity factor of wind turbines is predicted using equation Eq. (2).

$$CF_{j,i} = \frac{1}{LifeTime_j} \int_0^{LifeTime_j} P_j\left(v_{i,t}\right) d_t \tag{2}$$

In Eq. Eq. (2), $LifeTime_j$ is the lifetime of the wind turbine, $P_j\left(v_{i,t}\right)$ is the output power of wind turbine j at the speed $v_{i,t}$ (wind speed in region i at time t). To simplify the above relationship, it is possible to convert Eq. Eq. (2) into a discrete form by assuming that the wind speed is repeatable annually and by assuming that the wind speed is constant in at least one period of time.

Solving the optimization problem expressed by Eq. Eq. (1) determines the optimum wind turbine area. Next, based on the selection of the optimum wind turbine, the production of the power plant per hour $\left(P_j\left(v_{i,t}\right)\right)$ is estimated.

A.2. Solar power plant module

The solar power plant module is used to determine the optimal angle for installing solar panels, as well as the best time for installing them at that angle. By calculating the optimal installation angle at regular intervals, the amount of solar radiation that reaches the panel surface per hour can be estimated. The mathematical programming problem involves determining the installation angle and duration that result in maximum sunlight hitting the panel surface, while also considering the possibility of installing the panel at various angles. Both the proposed and conventional objective functions rely heavily on non-linear relationships. This problem can be expressed using Eq. Eq. (3) [59]. This optimization problem consists of 2m-1 decision variables and m linear constraints. m is the decision variable related to the optimum installation angle and m-1 is related to the period of installation on each angle. In the modeling done, it is assumed that the annual solar radiation does not change and is repeatable.

$$Max \sum_{i=1}^{x_1} EGTI_i\left(y_1\right) + \sum_{i=x_1+1}^{x_2} EGTI_i\left(y_2\right) + \dots \tag{3}$$

$$+ \sum_{i=x_{n-2}+1}^{x_{n-1}} EGTI_i\left(y_{n-1}\right) + \sum_{i=x_{n-1}+1}^{8760} EGTI_i\left(y_n\right)$$

s.t.

$$1 \le x_1 \le x_2 \le \dots \le x_{n_1} < 8760$$

$$x_1, x_2, \dots, x_{n-1}, y_1, y_2, \dots, y_n \ge 0,\ y_1, y_2, \dots, y_n \ge 90,\ Integer$$

In Eq. Eq. (3), $EGTI_{\theta,t,\alpha,\beta,\gamma}$ is the amount of radiation incident on the surface of the angled panel facing south in the northern hemisphere with an angle relative to the horizontal plane, at time t, located in latitude α, longitude is β with albedo γ. y_i is the angle of installation of the panel in $i-th$ choosing. Different models have been developed to calculate $EGTI$.

In the following, after calculating the angle and duration of installation for each time, the amount of radiation incident on the surface, and the amount of output electrical power are calculated. In this study, the effect of panel temperature on panel output power is ignored.

A.3. The optimum ratio module of two technologies

This module adjusts the optimum ratio of the two technologies in such a way that the capacity factor of the combined power plant is maximized based on the new definition of the capacity of the combined power plant, in other words, the difference between the maximum production value of the hybrid power plant in that region and the production value of the hybrid power plant in that region is minimized during the studied period. be made Since in practice, the construction of a solar power plant is more accessible than a wind power plant with any desired capacity, this ratio is calculated based on the capacity of the wind turbine. The selection of the optimum ratio is determined with the help of the mathematical programming problem expressed by Eq. Eq. (4). The optimization problem consists of two decision variables: the optimum ratio (α_i) and the practical capacity of the power plant in that area ($P_{maximum_i}$). The practical capacity of the power plant in that

$$Min\ Z_i = \sum_t \left(P_{maximum_i} - P_{WT,t,i} - \alpha_i\ P_{PV,t,i}\right) \tag{4}$$

s.t.

$$P_{WT,t,i} + \alpha_i\ P_{PV,t,i} \leq\ P_{maximum_i},\ \forall\ t$$
$$P_{maximum_i},\ \alpha_i \geq 0$$

In equation 4, $P_{WT,t,i}$ is equal to the normalized value of the output power of the wind power plant located in region i at time t and $P_{PV,t,i}$ is the normalized value of the output power of the photovoltaic power plant located in the region i at time t. The normalizing value of these two values is the maximum wind turbine production in that area. The capacity ratio of two power plants is calculated by equation Eq. (4) ($\alpha_i = \frac{P_{max,PV,i}}{P_{max,WT,i}}$), can not be equal to the real ratio of two power plants ($\beta_i = \frac{P_{Cap,PV}}{P_{Cap,WT}}$). This problem is due to the maximum difference in the amount of each technology production in a region.

Solar plant's capacity is based on the wind plant's capacity because of two reasons; Firstly, the intensity of the sun's radiation does not usually change significantly with a small shift in the installation coordinates of the power plant, provided that the effect of shadows is removed. However, the radiation potential may vary significantly. Secondly, the market offers a wide range of solar inverters, whereas the commercial capacity of horizontal axis wind power plants does not have the same scope as that of solar power plants. These factors play a crucial role in achieving the desired capacity of a solar power plant in a specific area. Consequently, the capacity of a solar power plant is often expressed in terms of the coefficient of the wind power plant.

B. The maximum energy harvested per square meter of land

If the access to the land for the construction of the power plant is an effective constraint (in other words, there is a need for minimum energy extraction per unit area), the hybridization of two wind and solar power plants can be effective. To identify the areas with the highest energy harvesting potential, the sum of the capacity factor of a wind power plant and solar power plant is used. The areas with the highest value of this factor indicate the higher energy harvesting potential per square meter of land, and to find the ratio of two power plants, the capacity of each power plant can be calculated independently.

3. RESULTS

In this research, 4900 points in Iran, mainly among the points close to Iranian settlements and cities, have been studied to identify areas with a high potential for hybridization. These points are analyzed to minimize the investment costs involved in developing transmission and distribution lines, lowering network losses, and reducing repair and maintenance expenses, the identified locations for investigation primarily include cities located near settlements.

In this study the optimization model for determining the optimal positioning angle of the photovoltaic panel was nonlinear using interior point method, and the selection model for the capacity ratio of two types of power plants is linear using Simplex method.

A. Providing base load or maximum capacity factor

According to the proposed structure, using the wind turbine module, the optimum wind turbine has been selected, and the approximate amount of wind turbine production per hour has been determined, then with the help of the solar module, the optimum installation angle of the photovoltaic panel and the amount of sunlight on the surface have been determined. In the third step, the optimum ratio is determined with the help of the capacity ratio optimization module.

First step: Optimum wind turbine and hourly production power

The optimum wind turbine has been selected among 15 wind turbines with a capacity of 1.5 MW to 8 MW with the highest capacity factor. The information on these 15 wind turbines is mentioned in Appendix. In more than 98.5% of the investigated points, the 2.5MW wind turbine manufactured by Axiona company, model G126-2.5MW, has the highest capacity factor. Although in other places, the 3MW wind turbine manufactured by Goldwind company, model GW140, has the highest capacity factor, the highest capacity factor in these areas was around 1.5% (in practice, it was not suitable to install wind turbines). In addition, after sorting from the lowest to the highest attainable value of the capacity factor (for 4900 investigated points), the classification into ten equal groups (from the point of view of number) has been made, and Fig. 2 shows the change interval of the capacity factor of each decile, and Fig. 3 shows the location of each of the deciles on the map. The color of each decile is the same in Fig. 2 and Fig. 3.

The results show a significant range of power factors in the 10th decile. In this decile, the wind turbine capacity factor changes in the approximate range of 20.8% to 42.8%, and the average wind turbine capacity factor in this decile is expected to be 24.5%, and approximately 12% of the investigated points have the capacity factor that can be obtained by the best wind turbine above 20%. This problem shows that the points with significant wind energy potential in Iran are limited. If the optimum wind turbine of the region is not selected, the capacity factor will decrease. The importance of choosing the correct and optimum wind turbine for each region can be shown by comparing the highest and the lowest capacity factor of wind turbines. The distance between the highest capacity factor and the lowest value reaches 30% in some places. Fig. 4 shows the

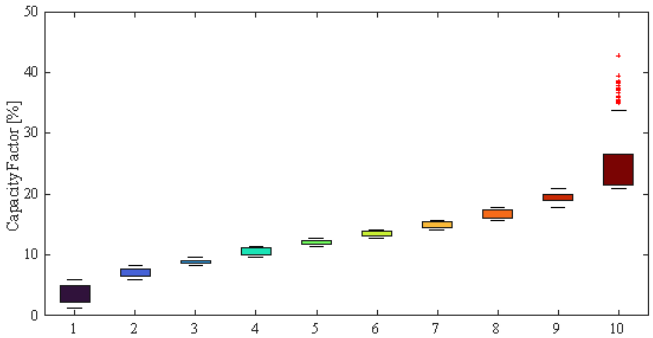

Fig. 2. The change interval of the wind turbine capacity factor of each decile

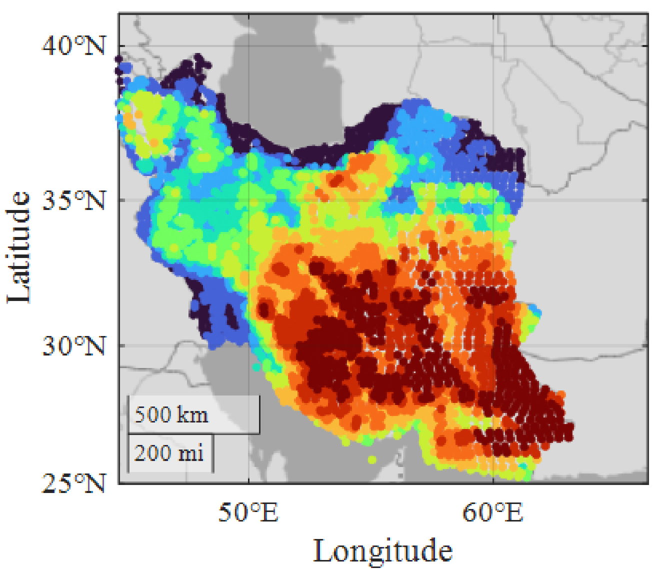

Fig. 3. Location of each wind turbine decile

difference between the highest capacity factor and the lowest capacity factor in the case of changing the wind turbine for each region.

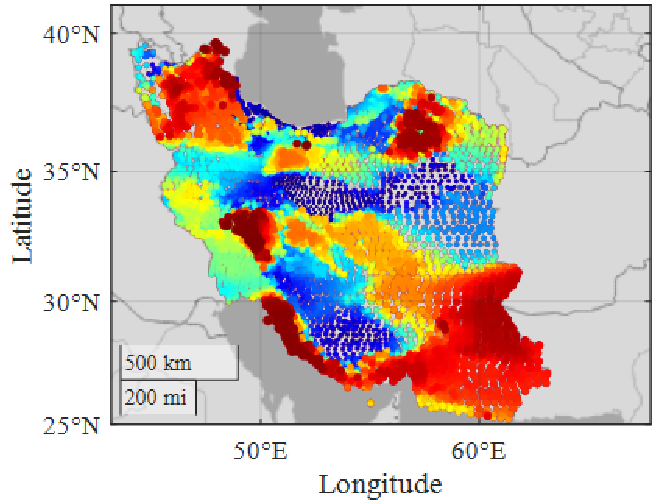

Fig. 4. The difference between the highest capacity factor and its lowest value

Second step: The optimum installation angle and the highest amount of solar radiation on the surface The optimum installation angle has been calculated with the aim of the obtained maximum incoming radiation on the surface with the possibility of installation on only one angle. Fig. 5 shows the range of annual radiation changes on the surface with installation at the optimum angle in each decile, Fig. 6 shows the change in the range of the panel's optimum installation angle in each decile, and Fig. 7 shows the location of each decile on the map of the country. In this Fig., the diameter of the indicator representing each decile is a function of the amount of annual radiation incident on the surface of the panel. The color of each decile is the same in Figs. 5 to 7.

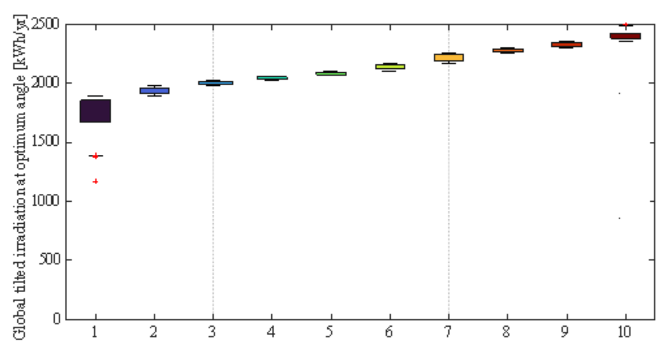

Fig. 5. The interval of change of annual radiation on the surface by settling on the optimum angle in each decile

Based on the information shown in Fig. 5, the range of variation of solar radiation intensity on the surface in 4900 investigated points is between 1171 $\left[\frac{kWh}{yr}\right]$ to 2517 $\left[\frac{kWh}{yr}\right]$ and the average radiation is 2118 $\left[\frac{kWh}{yr}\right]$. More than 95% of the examined points have annual radiation of more than 1752 $\left[\frac{kWh}{yr}\right]$ (in

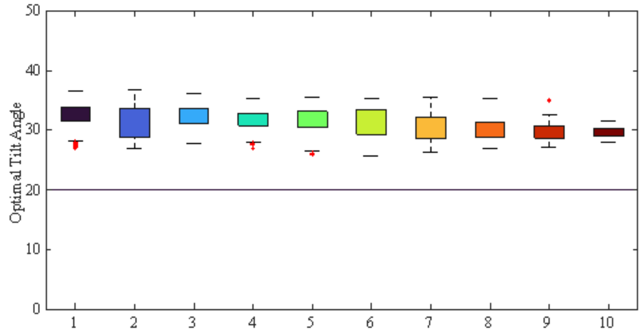

Fig. 6. The interval of changing the optimum installation angle in each decile

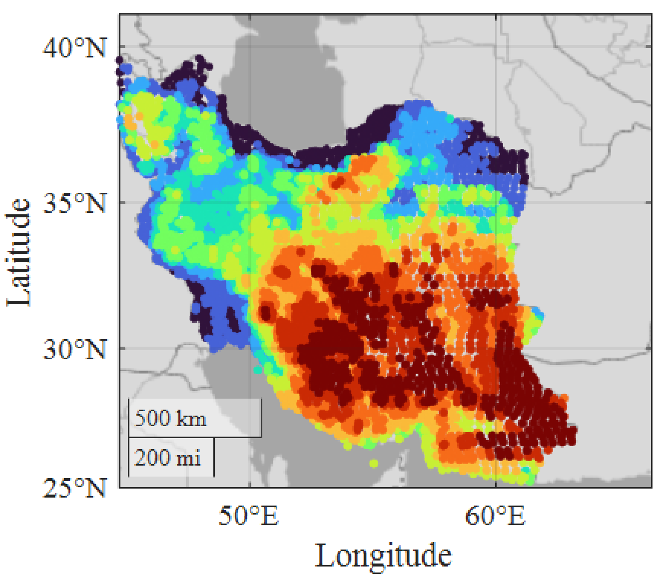

Fig. 7. Location of each radiation decile

other words, the nominal capacity factor is higher than 20%). This issue shows the potential of significant solar radiation in Iran. The range of changes in the annual intensity of radiation from the third decile onward is almost insignificant. This issue shows the uniform and high radiation potential in Iran.

To obtain the maximum radiation incident on the surface of a panel at its installed angle, the optimum angle change range is estimated between 25.7° and 36.7°.

Third step: With the help of equation Eq. (4), the ratio of the capacity of two power plants is determined in such a way that the total difference from the maximum output power of the hybrid power plant in each region is minimized, assuming the existence of the wind power plant as the base power plant. Therefore, it is expected this factor to be zero in many areas. Examining the results shows that the change range of the optimum ratio of the two power plants varies from zero to 22.8% based on the stated criteria for the 4900 investigated points. If the regions of the country are divided into 4 categories based on the ratio of two power plants (0% to 6%, 6% to 12%, 12% to 18%, and 18% to 24%), it can be seen that in more than 99% of the country's regions, this factor is within the range from 0 to 6%. Fig. 8 shows a graphical representation of the location of each category and the diameter of the marker indicates this ratio in each category.

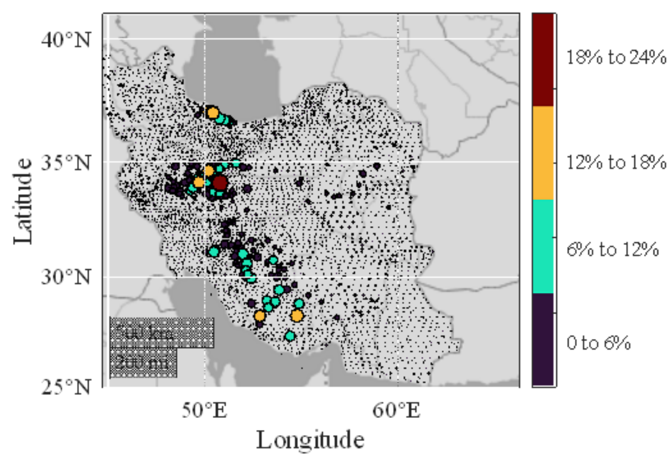

Fig. 8. The location of the category of each region from the point of view of the capacity ratio of the two power plants

The calculated low ratio makes this question that has the capacity factor of the hybrid power plant compared to the previous wind power plant able to change significantly? If the power plant capacity factor is defined based on the obtainable capacity based on the environmental conditions. This change is expected in the range of 0 to approximately 75%. Fig. 9 shows the effect of this change on the capacity factor. Although the limit of the defined interval shows the significant effect of the addition of the solar power plant on the capacity factor of the wind power plant, in a small share of the areas with the addition of the solar power plant, the capacity factor improves significantly. The results show that in more than 99% of the regions, with the addition of a solar power plant to a wind power plant, their capacity factor is improved by less than 18.75%. Although the change interval of the improvement of the capacity factor is estimated to be close to 75%, the maximum increase of the capacity factor is about 4%. This issue indicates that the added solar power plant has mainly affected areas with little wind potential. Fig. 10

shows an improvement percentage in the capacity factor of the hybrid power plant compared to the basic wind power plant.

In Fig. 10, the capacity factor of the wind power plant is calculated based on the maximum production power of the wind turbine in that area. As shown in this Fig., the calculated value is higher than the actual capacity factor of the wind turbine, and this value is higher mainly for areas with a lower capacity factor because in these areas the wind speed is lower than the nominal wind speed to obtain the nominal wind turbine power.

By comparing Fig. 9 and Fig. 10, it can be concluded that the addition of solar power plants to areas with significant wind potential does not make the production of wind and solar hybrid power plants uniform (improvement of the capacity factor of hybrid power plants).

B. Identifying the areas with the maximum energy harvesting potential per unit area

If the criteria for identifying areas prone to the construction of hybrid power plants is the obtained maximum production energy per unit area, the areas with the maximum total capacity factor of wind and solar power plants should be selected. Fig. 11 shows the map of the total capacity factor of wind and solar power plants in the examined points. The diameter of the marker indicates this sum. These areas are divided into ten groups with equal point sizes from the point of view of the defined factor change interval and are shown in Fig. 12.

According to Fig. 12, except for the first decile, the ninth, and the tenth deciles, the change interval of the defined factor is insignificant in other deciles. The points located in the 10th decile are the places prone to the construction of a hybrid power plant to achieve the maximum energy production per unit area.

4. CONCLUSION

Changes in environmental conditions such as wind speed and wind direction, solar radiation, temperature, and other similar things will affect the output power of wind and solar power plants. In this study, two models are introduced to identify areas prone to wind-solar power plant construction, and the effects of the mentioned factors on the output power of the power plant have been investigated. The first model is based on the obtained maximum capacity factor and the second model is based on the obtained maximum energy extraction per unit area.

Choosing the optimum capacity factor from two solar and wind power plants can result in the hybrid power plant's output power approaching the maximum production power of the hybrid power plant in that region (the maximum production power of the hybrid power plant in each region can be smaller than or equal to the total nominal capacity of both power plants). To achieve this goal, the structure of finding the optimum capacity ratio of two power plants consisting of three modules (solar, wind turbine, and optimum ratio of two power plants) was developed. The wind turbine module is used to select the optimum wind turbine for the region and the amount of wind turbine production in each period. The optimum selection criterion of the turbine used in this study was the obtained maximum capacity factor. The solar module has been developed to determine the optimum installation angle and the amount of radiation incident on the surface. Using the results of these two modules and a mathematical planning model, the capacity ratio of two solar and wind power plants is determined in such a way that the capacity of the hybrid power plant is maximized. In this case, the capacity of the power plant is the maximum capacity that can be obtained in the conditions of that climate in this research. According to the second model, the prone areas and the capacity ratio of two power plants are defined based on obtaining the maximum energy that can be harvested from two energy carriers per unit area. The factor defined to identify these areas is the algebraic sum of the capacity factor of two wind and solar power plants, and the ratio of the capacity of the two power plants is determined in such a way that the maximum capacity of each power plant is installed in the study area.

Using the developed model, wind potential, solar radiation, and optimum capacity factor of the 4900 points of Iran were selected with the priority of selecting all the cities and areas near the settlement. Investigations show that 95% of the investigated points have a solar power plant capacity factor exceeding 20%, while in about 12% of the investigated points, the wind turbine capacity factor is higher than 20%. Also, the range of solar radiation changes from the third decile onwards is almost insignificant, while most of the change in the range of the wind turbine capacity factor occurs in the tenth decile, and this problem indicates the high solar potential in contrast to the wind potential. Hybridizing these two technologies will not have much effect on improving the capacity factor in the areas prone to the construction of wind-solar power plants. According to the second model, less than 10% of the investigated points have significant potential from both technologies and the energy efficiency per square meter is significant.

Commercial technologies of electricity generation based on renewable energies mainly use solar, wind, water, and biomass. Among these four energy carriers, it is not possible to use water turbines in all regions of Iran, also biomass has a higher competitive advantage than the other three energy carriers due to the possibility of simple storage. The purpose of this study was to select two different energy carriers in one region to make electricity production uniform. The use of water and biomass energy carriers, due to the possibility of easier storage and control, provides the possibility of more uniform electricity production, which will be investigated in the future study of the method of hybridizing biomass and solar energy in Iranian cities.

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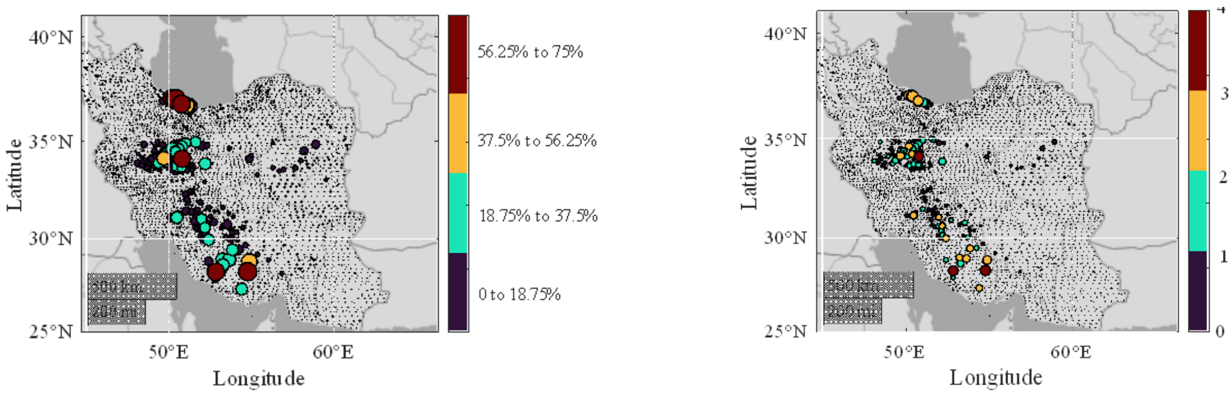

(a) The percentage improvement

(b) Load b

Fig. 9. The amount of improvement

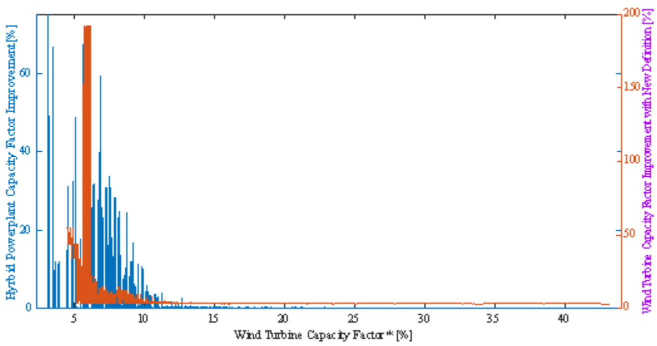

Fig. 10. The percentage improvement of the hybrid power plant capacity factor compared to the basic wind power plant

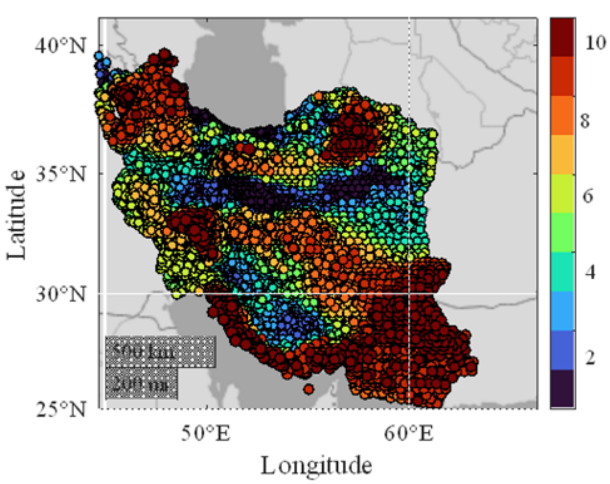

Fig. 11. The energy harvesting potential per unit area

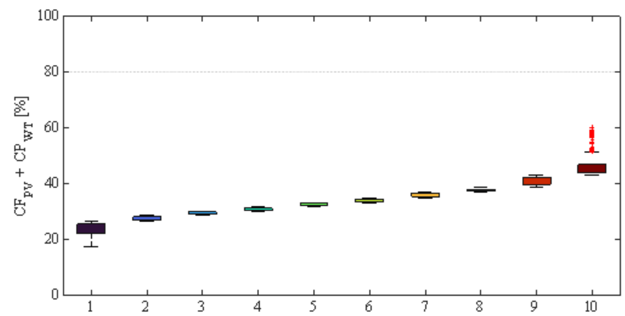

Fig. 12. The range of changes in the energy extraction factor per unit area in each decile

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APPENDIX

In Table 1, the key data of the 15 wind turbines examined in this study is shown.

Table 1. Key information of 15 studied wind turbines

#	Capacity	Manufacture	Model	Nominal wind speed (m/s)	Maximum wind speed (m/s)	Minimum wind speed (m/s)	Router Diameter (m)
1	1.5 MW	GE Energy	1.5xle	12.5	(m/s)	3.5	82.5
2		GE Energy	1.5s	13	25	4	70.5
3		GOLDWIND	GW 70/1500	11.8	25	3	70
4		GOLDWIND	GW 87/1500	9.9	22	3	87
5	2.3 MW	Siemens	SWT 2.3-108	11-12	25	3-4	108
6	2.5 MW	GOLDWIND	GW 109/2500	10.5	25	3	109
7		GOLDWIND	GW 121/2500	9.3	22	3	121
8		GE	TC 2/5-103	11.7	25	3	103
9		ACCIONA	G126-2.5 MW	9.9			126
10	3 MW	ENERECON	E-82 – E4	15-16	28-34	3	82
11		GOLDWIND		10.5	20	2.5	140
12	3.5 MW	GW 140	E-101	11-12	28-34	3	101
13	4.2 MW	ENERECON	E-126 EP4	13-14	28-34	3	127
14	7.58 MW	ENERECON	E-126	15	28-34	3	127
15	8 MW	Vestas	V164	12		4	164