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Research Article

Techno-economic performance assessment of central-grid wind turbines at major geographical locations of Pakistan

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Abstract: This work is focused on techno-economic performance evaluation of grid connected wind turbines of different power ratings (2 MW and 3 MW) at six coastline areas of Pakistan using RETScreen software. Software imports the weather data of selected locations from its database reported by National Aeronautics and Space Administration. Software outcomes indicate the unadjusted energy production, gross energy production and capacity factor of wind turbines. Comparative study shows that the wind turbine of either rating installed in Jiwani, having capacity factor 33.7% (of 2 MW turbine) and 36.8% (of 3 MW wind turbine) produces ~64% more gross energy than at Karachi and ~4% more than that at Ormara location. Financial viability of wind power project installation is evaluated considering economic determinants and life cycle savings. Technical analysis also reveals the amount of electricity exported to grid. Comparative performance of 3 MW and 2 MW wind turbines is evaluated, and 3 MW wind turbine is found more viable and profitable. Jiwani is found the most favorite location for wind power project installation.

Keywords: *Wind energy, Wind turbine, Capacity factor, RETScreen, Economics*

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Nomenclature	
V	Wind Speed
h	Height
ρ	Air density
P	Wind power
C_p	Power coefficient
GHG	Greenhouse gases
CF	Cash flow
CF_0	Zeroth cash flow i.e. investment
CF_i	i^{th} cash flow
NASA	National Aeronautics and Space Administration
NPV	Net present value
IRR	Internal rate of return
BCR	Benefit-cost ratio

1. INTRODUCTION

Energy plays a vital role in improving the living standard of a nation and to strengthen all economy concerned matters. Energy as a conserved quantity [1] is an important principle behind all science and engineering concepts. Its demand is increasing in an impressive way with continuous expanding urbanization and industrial revolution causing fast economic growth in the world [2]. Global primary energy demand has become almost double during last ~3 decades [3], and this increase is expected to be 53% by 2030 [4]. This continuous increasing energy demand was fulfilled by combustion of fossil fuels i.e. liquefied petroleum products (33.7%), coal (30.5%) and natural gas (24.4%) [4]. With continued current consumption rate, crude oil and natural gas reserves would run out by ~2052 and ~2073 respectively [5] that's why European Union included the production of innovative fuels as one of the main targets in Horizon-2020 projects [6]. In current world energy scenario, renewable energy systems are thought to be the best option to tackle the sustainability and global climate change issues [7]. Nature has gifted this world with several abundant and non-replenish-able sources of energy that are large enough to accomplish current overall energy requirements, and solar and wind are the most salient among them [8, 9].

Pakistan is one of the developing nations facing acute power shortfall, and is a part of 10 countries count that account for 66% of world's such population living without electricity access [10]. Pakistan's primary energy supply largely dependent on fossil fuels [11] i.e. natural gas (49.5%), liquefied petroleum products (30.8%). Total of only 10.5% [11] primary energy is supplied by hydel power. Unfortunately, renewable share of Pakistan energy mix is not even considerable in-spite of having immense wind and solar potential. Coastline areas of Sindh and Balochistan provinces that have maximum wind potential, suffered the worst power crisis situation since long. Still half of Sindh and nine-tenth of Balochistan province population has no access to electric power [10]. Up-to now six wind power projects of total 308.2 MW are in operational status and many projects of total 1140 MW are in installation or pipeline phase as elaborated in Table 2 [12]. Pakistan has ~1046 km long coastline, starting from Indian border in east to Iranian border in the west as depicted in wind map of Pakistan (Figure 1), that has poor to outstanding wind resource potential range against certain wind speed values as tabulated in Table 1 [13]. It is reported that Ghoro ~ Keti Bandar wind corridor spreading 60 km along the coastline of Sindh province and more than 170 km deep towards the land alone has potential of generating more than 60,000 MW [14] electric power.

Table 1. Wind power resource potential classification against certain wind speed [13]

Wind Power Class	Resource Potential	Wind Power Density at 50 m (W/m^2)	Wind Speed at 50 m (m/s)
1	Poor	0-200	0.0-5.4
2	Marginal	200-300	5.4-6.2
3	Fair	300-400	6.2-6.9
4	Good	400-500	6.9-7.4
5	Excellent	500-600	7.4-7.8
6	Outstanding	600-800	7.8-8.6
7	Superb	>800	>8.6

Table 2: Wind power projects in Pakistan [12)

Sr.#	Project Name	Capacity (MW)	Current Status
1	FFC Energy Limited	49.50	Operational
2	Zorlu Enerji Pakistan (Pvt.) Limited	56.40	Operational
3	Three Gorges Pakistan First Wind Farm (Pvt.) Limited	49.50	Operational
4	Foundation Wind Energy II (Pvt.) Limited	50.00	Operational
5	Foundation Wind Energy-I Limited	50.00	Operational
6	Sapphire Wind Power Company Limited	52.80	Operational
Projects Under Construction (Achieved Financial Close)			
7	Yunus Energy Limited	50.00	Signed EPA with CPPA/NTDCL and IA with GOP (AEDB)

8	Sachal Energy Development (Pvt.) Limited	49.50	Signed EPA with CPPA/NTDCL and IA with GOP (AEDB)
9	Metro Power Company Limited	50.00	Signed EPA with CPPA/NTDCL and IA with GOP (AEDB)
10	Tapal Wind Energy Pvt. Limited	30.00	Signed EPA with CPPA/NTDCL and IA with GOP (AEDB)
11	United Energy Pakistan Pvt. Limited	99.00	Signed EPA with CPPA/NTDCL and IA with GOP (AEDB)
12	Hydro China Dawood Power Pvt. Limited	49.50	Signed EPA with CPPA/NTDCL and IA with GOP (AEDB)
13	Master Wind Energy Limited	49.50	Signed EPA with CPPA/NTDCL and IA with GOP (AEDB)
14	Tenega Generasi Limited	49.50	Signed EPA with CPPA/NTDCL and IA with GOP (AEDB)
15	Gul Ahmed Wind Power Limited	50.00	Signed EPA with CPPA/NTDCL and IA with GOP (AEDB)
Projects in Pipeline			
16	Jhampir Wind Power Limited	50.00	Signed EPA With CPPA/NTDCL, Negotiation yet to be started
17	Hawa Energy Pvt. Limited	50.00	Signed EPA With CPPA/NTDCL, Negotiation yet to be started
18	Hartford Alternative Energy Pvt. Limited	50.00	Stage not reached yet
19	Three Gorges Second Wind Farm Pakistan Limited	49.50	Stage not reached yet
20	Three Gorges Third Wind Farm Pakistan (Pvt.) Limited	49.50	Stage not reached yet
21	Tricon Boston Consulting Corporation (Pvt.) Limited (A)	50.00	Stage not reached yet
22	Tricon Boston Consulting Corporation (Pvt.) Limited (B)	50.00	Stage not reached yet
23	Tricon Boston Consulting Corporation (Pvt.) Limited (C)	50.00	Stage not reached yet
24	Zephyr Power Pvt. Limited	50.00	Stage not reached yet
25	Western Energy Pvt. Ltd	50.00	Stage not reached yet
26	China Sunec Energy (Pvt.) Limited	50.00	EPA & IA Negotiation yet to be started
27	Burj Wind Energy (Pvt.) Limitd	14.00	Stage not reached yet
28	Trans-Atlantic Energy (Pvt.) Limited	50.00	Stage not reached yet
29	Shaheen Foundation PAF	50.00	Stage not reached yet

Current study aims to have a detail life cycle analysis of grid connected wind turbines having different power ratings (2 MW and 3 MW) using RET Screen wind energy model at six major latitude locations selected at Pakistan wind corridor named: Karachi, Hyderabad, Badin, Jiwani, Ormara and Gwadar. Three of selected locations are a part of Balochistan province coastline named: Jiwani, Ormara and Gwadar; while remaining three belong to Sindh province. Work is focused on:

Comparative performance evaluation of wind turbines having different power ratings in terms of their technical parameters i.e. capacity factor, gross energy production and electric power exported to grid.

Economics of modelled systems is evaluated on the basis of determinants i.e. IRR, payback period, NPV, BCR and life cycle savings.

Analysis also reveals how much GHG emissions reduction is possible?

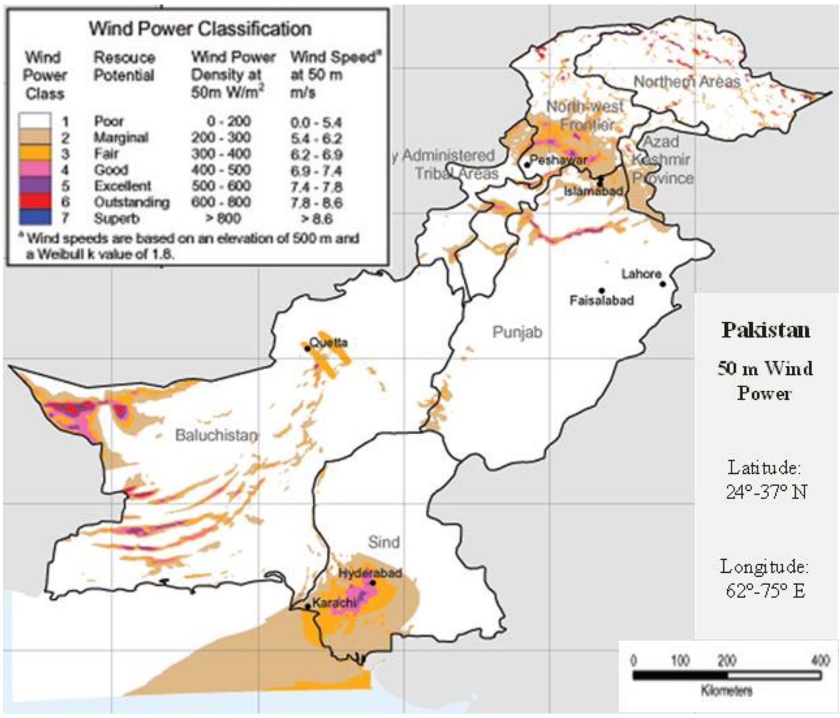

Figure 1. Wind power density map of Pakistan [13]

2. CLIMATE INFORMATION OF SELECTED LOCATIONS OF PAKISTAN

Climate information of any location means a lot in case of renewable energy projects. In wind projects evaluation; wind speed is one of the most important weather information that is actually an input force. RET Screen software imports the climate information of any selected location from its database reported by NASA. Climatic information of different coastline areas selected for current study are tabulated in Table 3.

Table 3. Climatic information of wind turbine project sites in Pakistan.

Property	Climatic data of the location					
Location	Karachi	Hyderabad	Badin	Jiwani	Ormara	Gwadar
Latitude (°N)	24.9	25.4	24.7	25.1	25.2	25.1
Longitude (°E)	67.1	68.4	68.8	61.8	64.6	62.3
Ambient temperature (Annual) °C	26.1	26.5	27.0	25.5	24.6	25.2
Average annual wind speed (m/s) [measured at 10 m]	3.5	3.5	3.2	4.1	4.0	4.1
Atmospheric pressure-annual (kPa)	100.6	99.9	100.5	98.0	97.6	98.0

3. METHODOLOGY TO EVALUATE THE WIND TURBINE PERFORMANCE

RETScreen software based on f-chart method, developed by Natural Resources Canada’s CANMET Energy Diversification Research Laboratory (CEDRL), is used worldwide to figure out the viability of potential renewable energy based projects at the first. In current work, techno-economic viability of 2 MW and 3 MW wind turbines at different coastline areas is carried out using wind energy model of RETScreen software. The methodology adopted to evaluate the performance of central-grid wind turbines case study is shown in Figure 2; involving all input parameters and estimated outcomes.

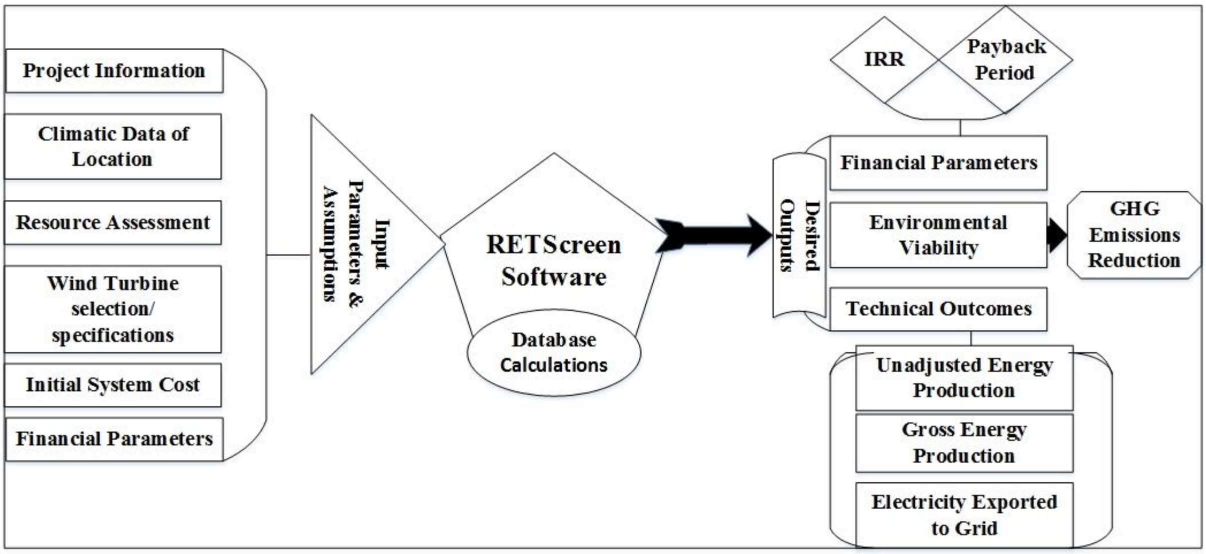

Figure 2: Methodology adopted to evaluate the comparative performance of central-grid wind turbines.

Wind is one of the cleanest technologies being and could be used for power generation. Wind turbine is the key element of any wind power project. That's why a lot of work has been carried out concerned with wind turbine size and still continues. In start to the mid of 1980's, available wind turbine size was less than 100 kW [15]. By the end of 2nd last decade of 19th century, this available wind turbine size had increased to 500 kW [15]. After that, wind turbine size increased progressively and reached to 1000 kW by mid-1990s. Now turbines with more than 8 MW generation capacity having 180 m rotor diameter have been manufactured [16].

The wind is fuel- unlike fossil fuels it is both free and clean, but otherwise it is just the same. It drives the wind turbine that exports electric power to grid. Windmill power generation requires continuous wind flow at a rated speed. This is very difficult because wind speed fluctuates over short period of time and dependent on height above the ground. Wind speed at certain height above the ground can be estimated using Hellmann exponent law [17];

$$V(h)/V_{10} = (h/10)^{\alpha}\alpha \qquad (1)$$

In equation (1), $V(h)$ represents the wind speed at any certain height while V_{10} is wind speed at height of 10 m. The Hellmann exponent's (α) value is function of roughness of terrain, but in case of flat-open country this exponent's value is equivalent to one seventh. The available power in wind at any speed rate per unit area can be estimated using [18];

$$P = 1/2\rho V^3 \qquad (2)$$

It is not possible to extract the total available wind power by any wind machine. So the maximum power could be extracted through any wind machine is limited by Betz relation [18]. The maximum extractable power per meter is estimated using following relation;

$$P_{\max} = 1/2\rho C_p V^3 Wm^{-2} \qquad (3)$$

In Equation 3; C_p is power coefficient assigned by Betz relation equivalent to 16/27 for the maximum wind machine performance. Efficiency of some common types of wind turbines against tip speed ratio (tsr) is depicted in Figure 3 [19].

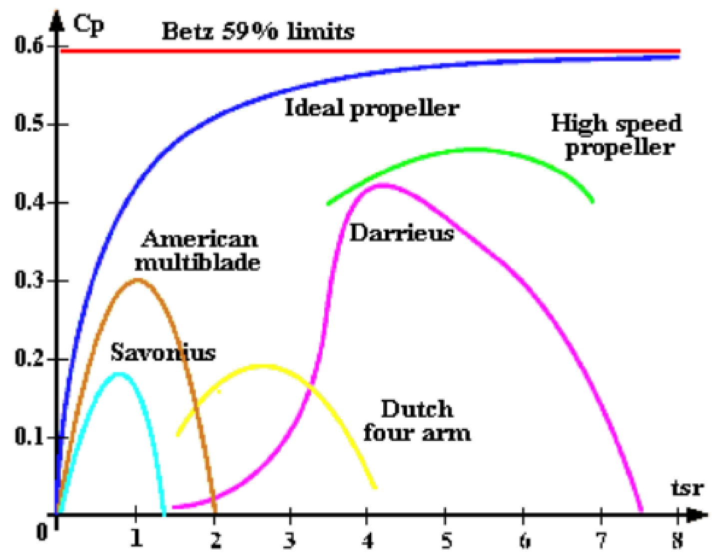

Figure 3. Efficiency of some wind turbines against tip speed ratio [19]

Input parameters used for evaluating the performance of wind turbines of different ratings are listed in Table 4 and
Table 5. Wind turbine selection is made keeping in view its characteristic features suitability and concern of availability. Financial input parameters required by software to figure out the viability of wind turbine system involves; electricity export rate announced by National Electric Power Regulatory Authority equals to 16.207 PKR/kWh [14], average fuel cost escalation rate that is 4.10% [20] in Pakistan, average inflation rate equals to 2.26% [20], discount rate has been raised to 9.5% by State Bank of Pakistan, and interest rate currently exists in bank trading is 6.0% [21]. The total project investment including engineering, procurement and construction (EPC) cost and non-EPC costs estimated equals to 255.016 PKR Million/MW [22].

Table 4. Characteristic parameters of selected wind turbines.

Parameters	**Units**	**Value**	
Power capacity	MW	2	3
Hub height	m	108	135
Rotor diameter of turbine	M	82	101
Swept area per turbine	m^2	5,281	8,012

Table 5. RETScreen wind energy model input financial parameters.

Factor	**Value**
Total project cost	255.016 PKR Million/MW
Electricity export rate	16.207 PKR/kWh
Fuel cost escalation rate	4.10%
Inflation rate	2.26%
Discount rate	6.0%

4. RESULTS and DISCUSSIONS

Results based on system's unadjusted energy production, gross energy production, electricity exported to grid, project IRR, payback periods, NPV, BCR, life cycle savings, and GHG emissions reduction are presented and discussed in this section. These results are discussed in the following sections: Technical Analysis, Economic Behavioural Study, Environmental Effect.

4.1. Technical analysis

Technical performance assessment of wind turbines is carried out in terms of unadjusted energy production, gross energy production, capacity factor and electric power exported to grid.

Power produced by a wind turbine is largely depends upon speed of wind that causes the turbine rotor motion. As we move above the ground surface, wind speed increases progressively with the increase in height as shown in Figure 4. The comparison of wind speed curves for 10 m and 108 m heights shows that there is ~34% increase in wind speed against 98 m change in height. Furthermore, the analysis of wind speed curves for 108 m and 135 m heights elaborates that wind speed increases by 42~45% against 27 m further increase in height after 108 m altitude.

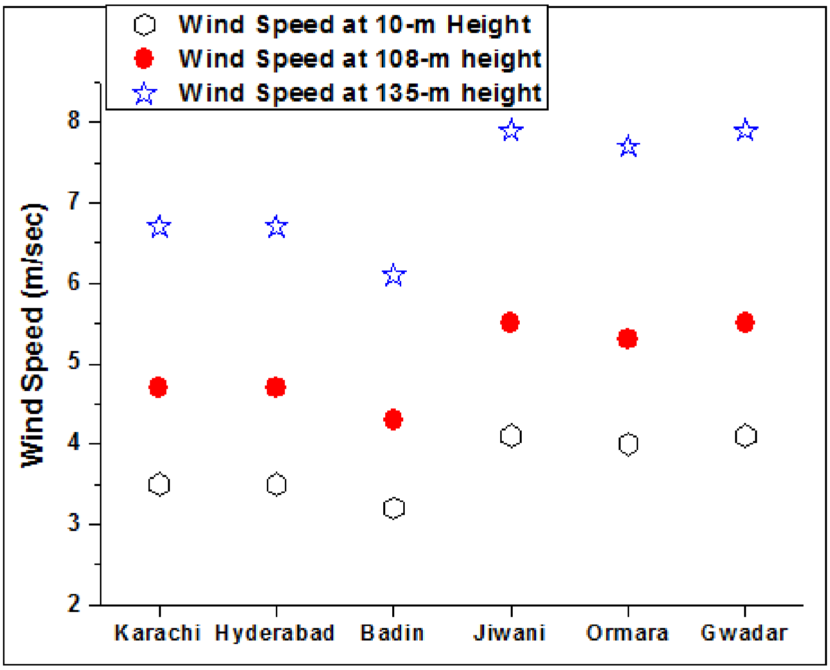

Figure 4. Variations in wind speed against height above the ground

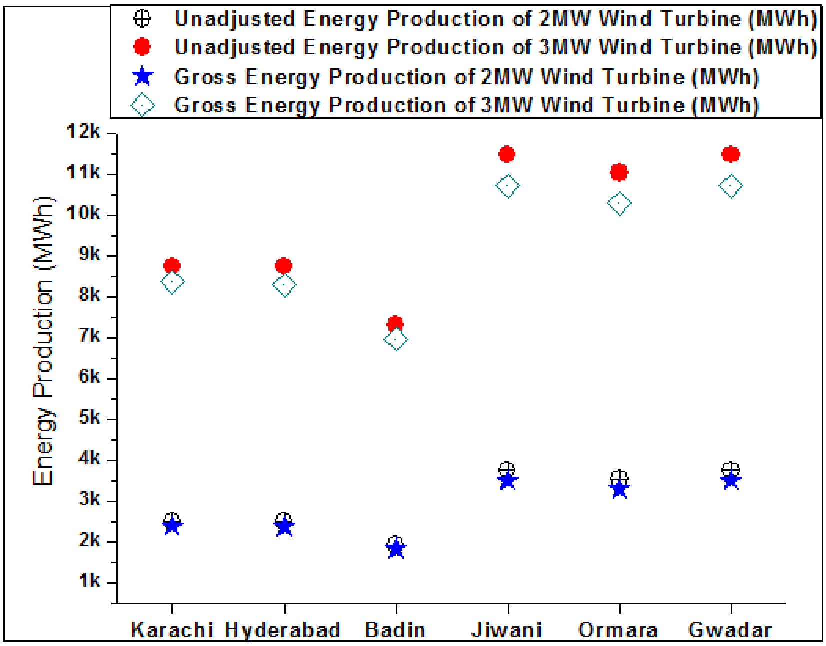

Figure 5. Unadjusted and gross energy production of wind turbines.

Unadjusted energy and gross energy produced by either of two different power rated wind turbines are depicted in Figure 5, while capacity factor of each turbine at certain location and final electricity exported to grid by each of gird connected wind turbines are shown in Figure 6. Analysis of these figures shows that the energy produced and final exported electric power to grid by either of the turbines at certain location directly correspond to available wind speed i.e. greater the value of wind speed

available, larger would be the value of gross energy produced and consequently higher MWhs would be exported to grid. Capacity factor of wind turbine is another indication parameter of wind turbine's performance. Higher the value of capacity factor means greater would be the amount of electric power exported by installed wind turbine to grid as evident in Figure 6.
Comparative technical analysis of Figure 5 and Figure 6 shows that Jiwani and Gwadar are the most favorable locations among all with highest capacity factor and maximum exported electric power values for both 2MW and 3MW rated wind turbines, while Badin is the least feasible one. Comparative study of two provinces elaborates that all the three under-examined cities of Balochistan province are technically more viable for wind turbine installation with ~35% greater electric power generation value and collectively 19~28% higher capacity factor compared to the cities of Sindh province outcome.
The comparative performance study of different power rated wind turbines shows that the wind turbine with 3 MW power rating is more technically viable than 2 MW wind turbine with 15~19% higher capacity factor. Electricity exported to grid by 3 MW wind turbine is 205~280% greater in value than that of 2 MW wind turbine. Reason associated with the fact is greater the height of turbine hub due to which speed of wind strikes the 3 MW turbine rotor is 42~45% higher in value than that strikes to 2 MW wind turbine rotor.

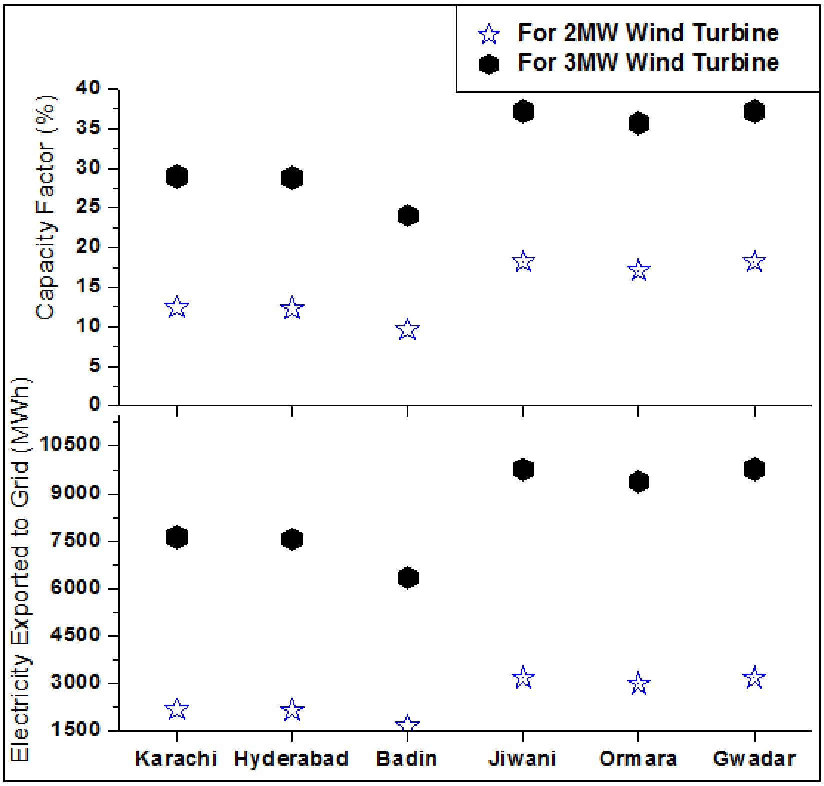

Figure 6. Capacity factor and electricity exported to grid by wind turbines

4.2. Economic behavioral study

Economic analysis of wind turbines having different power ratings is carried out considering economic determinants i.e. IRR, payback period, NPV, BCR and life cycle savings as deciding parameters, to find out whether it is financially viable to install a wind turbine at certain location or not?
IRR and NPV are the most influencing economic determinants according to economist approach, where IRR is a form of discounted rate that equals the net present value of a project cash flows to zero and often is used in capital budgeting. While NPV meant for coming cash flows that are subsidized at certain discount rate. These economic determinants can be calculated using [23];

$$-CF_0 + \sum_{i=1}^{t}\left[\frac{CF_i}{(1+r)^i}\right] = NPV = 0 \qquad (4)$$

Where; i= 1, 2, 3…, t

Payback period and annual life cycle savings are important economic determinants for a project with respect to investor's insight. Payback period tells about the time length to recover initial investment of the project. It can be calculated simply by dividing the project cost to annual cash flows. On other hand, annual life cycle savings account for nominal yearly based savings that are calculated considering project's NPV, project proposed life period and discount rate value.

Analysis of Figure 7, Figure 8, Figure 9 and Figure 10 show that all economic determinants favor the Jiwani and Gwadar locations the most for either of two different power rated wind turbines installation with maximum IRR values, minimum payback periods and relative higher values of NPV, BCR and life cycle savings. Badin is economically least feasible location with minimum values of IRR, NPV, BCR and life cycle savings, and maximum payback period.

In perspective of comparative analysis between Balochistan and Sindh provinces, it is concluded that all the three coastline locations of Balochistan province are economically more viable than of Sindh locations in terms of all economic determinants with higher NPV values, 16~17% greater IRR values, collectively 35~57% less payback periods, 0.93~1.39 greater BCR values, and relatively higher life cycle savings are possible (evident from Figure 7, Figure 8, Figure 9 and Figure 10).

The comparative analysis of wind turbines having different power ratings shows that wind turbine having 3 MW power rating is more viable to install than 2 MW wind turbine with positive NPV values, 11~13% higher IRR values, 52~60% less payback periods, and 0.71~0.94 higher BCR for all selected locations of Pakistan. Even life cycle savings are possibly positive only in case of 3 MW wind turbine installation compared to 2 MW wind turbine. It is also economically more profitable to install 3 MW wind turbine in Balochistan province territory as payback period curve for 3 MW wind turbine shows sharp decline for Jiwani, Ormara and Gwadar; on other hand curves representing NPV, BCR and life cycle savings for 3 MW wind turbine influentially raises for three latitude positions of Balochistan province compared to the curves for Sindh province locations (evident from Figure 7, Figure 8, Figure 9 and Figure 10). The reason that makes a system economically favorable or unfavorable is its technical outcomes: higher capacity factor value leads to greater energy production that will consequently result in greater amount of electric power exported to grid and vice versa.

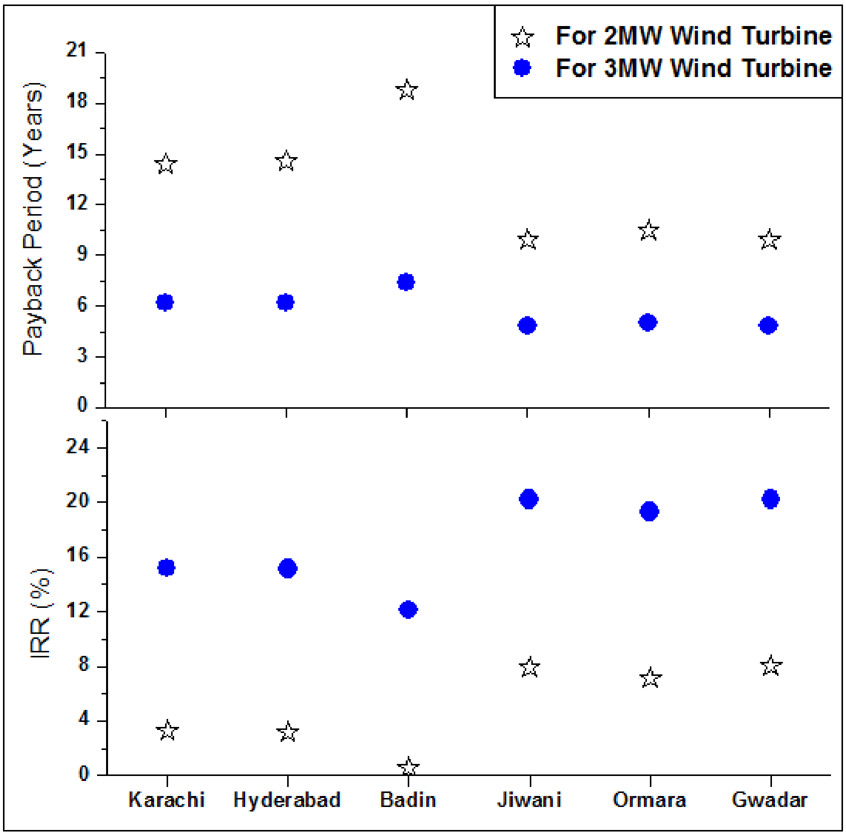

Figure 7. Economic behavioral study of wind turbines in terms of IRR and payback period

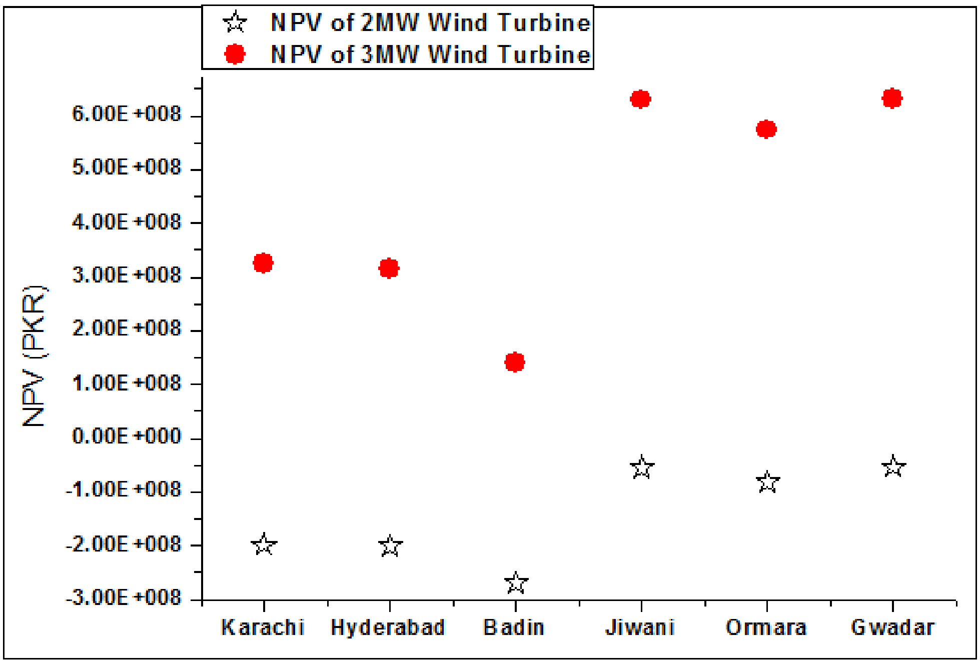

Figure 8. Project NPV of different power rated wind turbines for selected locations

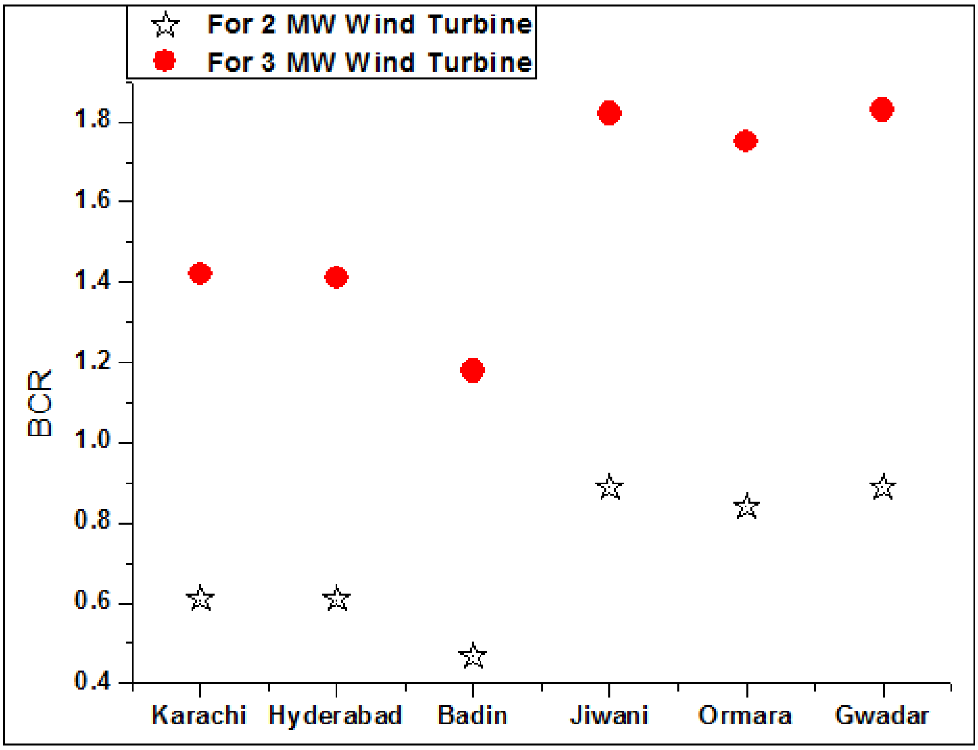

Figure 9. Benefit-cost ratios of 2 MW and 3 MW wind turbines

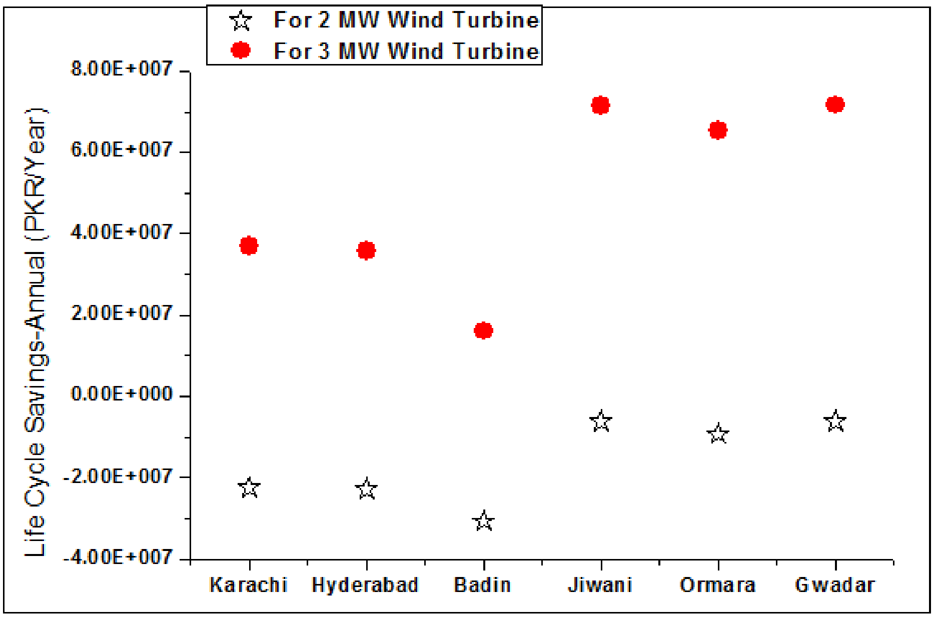

Figure 10. Life cycle savings due to 2 MW & 3 MW wind turbine installation

4.3. Environmental effect

GHG emission is a great concern for the entire world. It remained the most discussed issue particularly during last decade, that's why many protocols and standards have been set to control the emissions. Wind is the one of the cleanest technologies among all fuels including both renewables and non-renewables. GHG emissions reduction possible through installation of either of the two different power rated wind turbines at any of the selected locations is depicted in Figure 11. Analysis of Figure 11 shows that 400~900 tCO_2 and 1600~2600 tCO_2 GHG emissions could be reduced through installation of a 2 MW and 3 MW wind turbine respectively. The comparative analysis of two different power rated wind turbines reveals that the installation of a 3 MW wind turbine results in 205~280% greater GHG emissions reduction at certain location than that of a 2 MW wind turbine. The reason of this enhanced GHG emissions reduction value is exported amount of electricity produced by wind turbine instead of fossil fuel consumption.

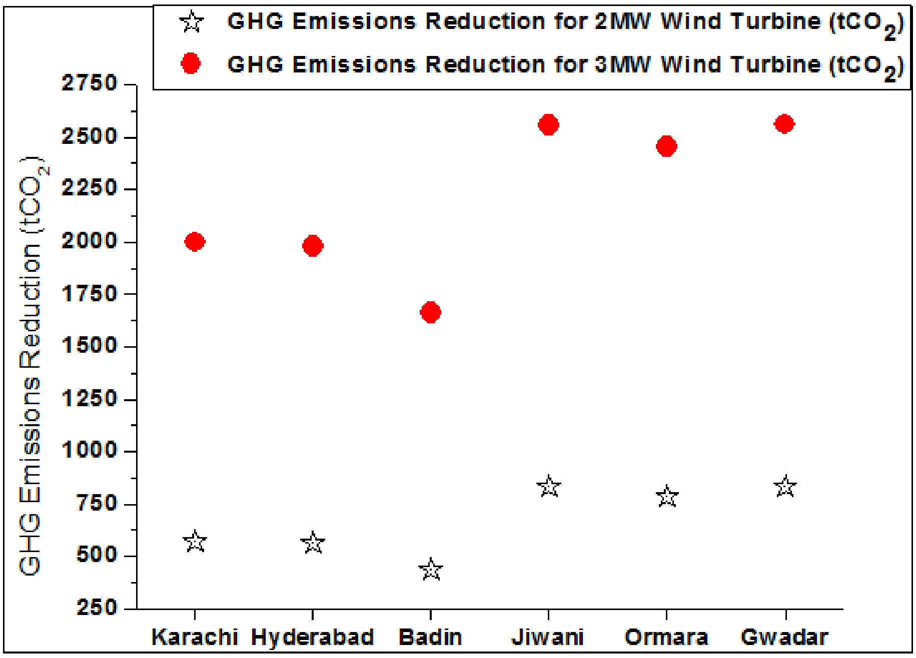

Figure 11. Environmental effect of wind turbine installation in form of GHG emissions reduction

5. CONCLUSIONS

Performance of wind turbines having 2 MW and 3 MW power ratings is evaluated using RETScreen simulation approach at six selected coastline areas of Pakistan. For this purpose, a new simulation methodology is developed that can be used for evaluating technical and especially economic perspectives of any wind energy model. After analyzing the technical, financial and environmental aspects of RETScreen wind energy model, it is concluded that Jiwani and Gwadar are the most feasible coastline areas while Badin is the least feasible for either of wind turbines installation. Among Balochistan and Sindh provinces, Balochistan has more attractive coastline for wind technology installation than of Sindh with positive NPV and life cycle savings stats. It is revealed that after a certain height above the ground, increase in wind speed is much progressive than in the start as moving from 10 m to 108 m accompanies only 34% increase, while moving from 108 m to 135 m height above the ground accompanies 42~45% increase in wind speed.

The comparative performance analysis of 2 MW and 3 MW wind turbines revealed that 3 MW wind turbine is 15~19% more efficient in terms of capacity factor and produces 205~280% more electric power with consequently positive NPV and life cycle savings stats, greater than one BCR values, 52~60% less payback period compared to that of 2 MW wind turbine with negative NPV values and less than one BCR values. Also installation of either power rated wind turbine would result in appreciable GHG emissions reduction lies in 400-2600 tCO_2 range.

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