Environmental and Health Risk Assessment of a Coal Fired Power Plant-Effect of Stack Height

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ABSTRACT

The coal fired power plants have well recognized environmental and health concerns all over the world. This study determines the effect of stack height on ground level concentrations of nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and particulate matter (PM) within the five-kilometer radius of a coal power plant. Pollutants dispersion was calculated using the air dispersion modelling at three stack heights (100, 150 and, 180-meters) of the power plant. Subsequently the health risk from SO_2 and PM2.5 was determined within five km radius by calculating the hazard quotient (HQ). Results indicate that 24-hour average concentrations of SO_2 at 100 m (159.75 μg/m³) and 150 m (125.06 μg/m³) and, NO_2 at 100 m (87.26 μg/m³) stack height exceeds the limits of National Environmental Quality Standards (NEQS). Similarly, the annual average concentrations of NO_2 (45.23 μg/m³) at 100 m and, PM2.5 at 100 m (28.86), 150 m (28.77 μg/m³) and 180 m (28.74 μg/m³) stack heights exceed the NEQS limit. At all stack heights the 24-hour average dispersion of PM2.5 and SO_2 poses a potential health risk. Overall this study recommends a stack height of 180 m to minimize the environmental and health risks of the pollutants from coal power plant.

1. INTRODUCTION

Air pollution from coal fired power plants have globally recognized environmental and health concerns, that must be properly spoken and addressed while planning and commissioning the new coal-based power plants. Coal is the fossil fuel formed by processing of prehistoric flora accumulated in swamps and peat bogs and, the energy content of coal is attributed to the photosynthetic solar energy absorbed by the coal forming plants [1]. Coal accounts for about 27 percent of the global primary energy and the current share of coal in global electricity production is about 38% [2].

For electricity production, coal is burnt at high temperature in a boiler and the heat energy produced from coal burning is used to convert the water into steam. This pressurized steam drives a steam turbine and the generator associated with turbine produces electricity [3].

Based on the type of boilers, currently three main types of coal-fired power plants are commonly used worldwide including, pulverized coal (PC) boilers, circulating fluidized bed (CFB) boilers, and integrated gasification combined cycle (IGCC) systems [4]. Based on the combustion technology coal power plants are classified as supercritical working at 600°C temperature and about 250 bar pressure and subcritical operating and 538°C and around 165 bar pressure [5].

Coal combustion for electricity production generates significant amounts of conventional and hazardous air pollutants such as, oxides of sulphur and nitrogen, particulates, arsenic and mercury etc. [6]. Air pollution released from the coal fired power plants is among the major environmental concerns mainly because of their long-term atmospheric movements and adverse impacts on atmospheric visibility, human and ecosystem health and cultural heritage [7]. Coal power plants also have significant contribution in greenhouse gas emissions and subsequent global warming and climate change [8]. Working of coal power plants also release significant quantities of wastewater, ashes and slags having toxic metals such as lead, arsenic and mercury and other pollutants etc that can potentially damage the soil, ground and surface quality and ecosystems [9].

World Health Organization (WHO) reports an estimated deaths of 7 million people per year in Africa and Asia [10]. Many countries report a high level of particulates and other air pollutants from coal burning usually exceeding the acceptable limits of the respective local and international environmental standards such as the world health organization (WHO) [11,12]. For instance, according to the

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global power emissions database the discharges of nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and particulate matter (PM_{10} and $PM_{2.5}$) from coal power plants accounted for 32.4%, 28.4%, and 7.3% respectively of the total emissions in China [13]. Similarly, in India; the second-largest coal consumer in the world, the air quality often remains poor in many parts of the country mainly due to coal-based power plants and brick kilns [14]. Currently most of the developing countries are implementing strict regulations for air emissions from coal power plants [15] whereas, many developed countries such as United States, Germany and Australia are transitioning from coal to renewable energy sources [16].

The air pollutants released from the coal power plants had been associated with the variety of acute and chronic illnesses among people and even deaths in severe cases [17]. Sulphur dioxide (SO_2) for instance, may cause eyes, throat and nose irritations and lungs diseases. Long term exposure to SO_2 is also associated with life threatening lungs cancer and cardiopulmonary diseases [18]. Research also reveals that the short-term exposure to NO_2 increases the respiratory diseases in children and asthmatic patients whereas, the long-standing contact to this pollutant may aggravate the respiratory infections by lowering the resistant in patients [19]. Studies also show a strong relationship between short-range contact to particulate matter (PM) and diseases and mortality in human [20].

Total amount and nature of the pollution generated from a typical coal power plant is mainly associated with the raw coal composition and coal combustion technology used in the power plant [21]. Dispersion and movement of pollutants released from coal power plants is highly dependent on the height of pollutant stacks [22]. Research shows that ground level concentrations (GLCs) of air contaminants from coal power plants is significantly changed with the changing heights of stacks in a power plant [23]. Generally, the higher stacks can increase the dispersion of air pollutants by promoting the dilution and greater atmospheric mixing. An increased stack height provides a better vertical momentum to the pollutant emissions, allowing them disperse over a larger area [24]. However, the meteorological conditions of the area highly influence the effectiveness of the stack height. Generally, the stack heights in stable atmospheric conditions, are not much effective in dispersing pollutants, as most of the pollutants in this condition remain trapped close to the ground. Moreover, the speed and direction of wind also found to have the impact on the effectiveness of stack height [25]. It is important to note that beside the increasing stack heights, additional control measures such as the use of scrubbers, improved combustion efficiency and use of low-emission fuels can also play a significant role in reducing air pollution from coal fired power plants [26]

Worldwide the air dispersion models are considered easy and cost-effective means to estimate wide spatial variation of air pollutants [27]. The source data in an air dispersion model is evaluated in conjunction with meteorological information such as wind direction and speed and ambient temperature etc. [28]. In addition to the measured meteorological parameters, most of the air quality models also require atmospheric stability classes and mixing height data [29]. Currently Gaussian models such as the US Environmental Protection Agency Regulatory Model (AERMOD) are commonly used air pollution dispersion models all over the world [30].

Present study provides an assessment of environmental and health risk associated with the air emissions from a coal-based power plant located in Pakistan. AERMOD model was used to determine the dispersion and ground level concentrations of NO_2, SO_2, $PM_{2.5}$ and PM_{10} released from the coal power plant at three different stack heights (100 m, 150 m, and 180 m). Subsequent assessment of health risks from SO_2 and $PM_{2.5}$ on the selected human receptors was carried in the locality of power plant.

This manuscript systematically provides the i) background concentration of the selected air pollutants within the five-kilometer vicinity of the coal power plant, ii) a comparison of background pollutant concentrations with the national environmental standards and environmental requirements of the World Health Organization (WHO) and World Bank (WB) iii) results of the air dispersion modeling i.e. the ground level dispersions of the selected air pollutants at various locations within the five km radius of the power plant iv) an assessment of incremental concentrations of the pollutants by adding the background concentration and concentration released from the coal power plant and v) finally an assessment of health risk of SO_2 and $PM_{2.5}$ on selected receptors within the vicinity of coal power plant.

Currently a small amount of literature was found related to the effect of stack heights on pollution dispersion from coal power plants and their risk for human health. Present study provides an insight for the environmentally and socially sustainable designs of coal power plants by considering the suitable stack heights.

2. MATERIALS AND METHODS

The studied coal fired power plant is based on pulverized supercritical technology having installed capacity of 660 MW. Estimated coal consumption for the power plant is about 6,000 tons/day. Location of the power plant is shown in Figure 1.

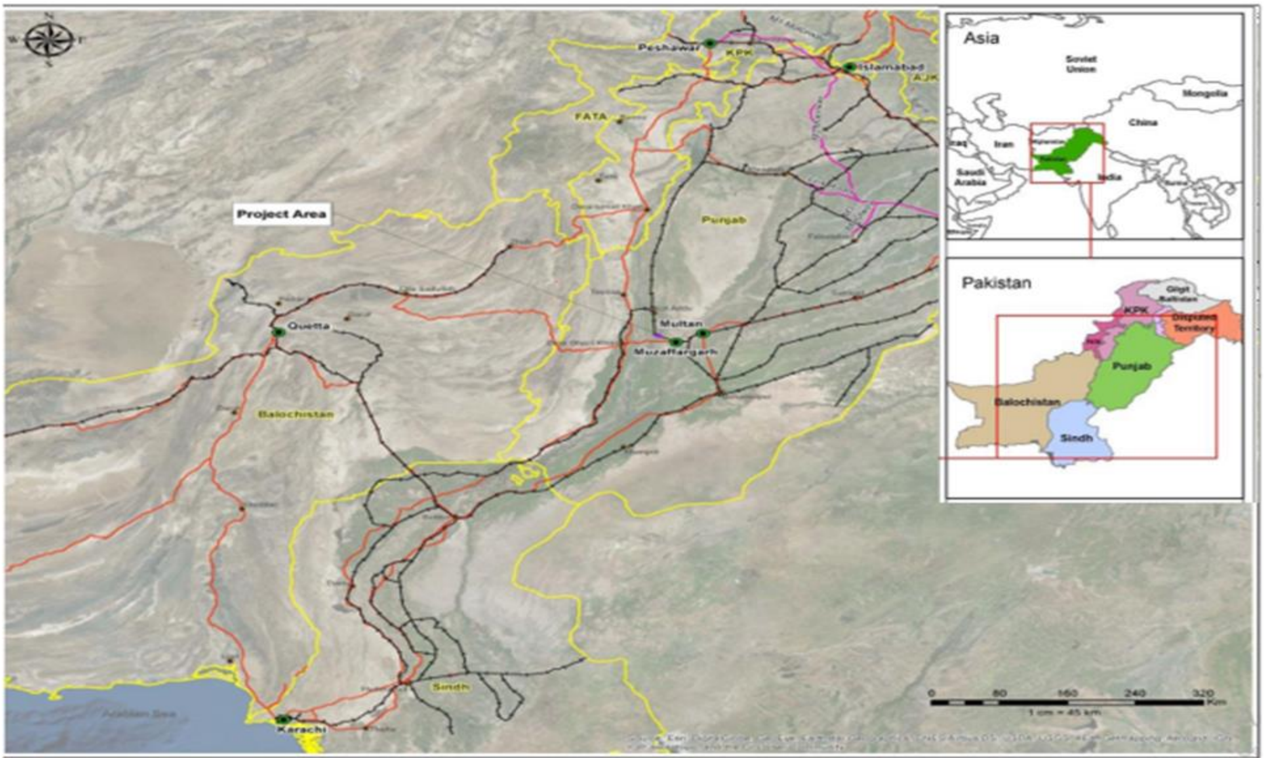

Fig. 1. Location map of the studied coal power plant.

Table 1. Methods and equipment used for baseline air quality analysis in the area of coal fired power plant

Pollutants	Method	Name of Equipment	Principle of Operation
NO_2	Chemiluminescence	Analyzers with Calibrator	Chemiluminescent Method
SO_2	Fluorescence Method	Analyzer with Calibrator	Ultraviolet (UV) fluorescent
PM_{10}	Beta Source	High Volume Samplers with PM_{10} Size Inlet	Gravimetric monitoring
$PM_{2.5}$	Beta Source	High Volume Samplers with $PM_{2.5}$ Size Inlet	Gravimetric monitoring

Table 2. Emission source data of the coal based power plant used for air dispersion modeling.

Parameter	Unit	Value	Notes
Fuel type		Coal	-
Sulphur content	%	0.9-1	
Ash content	%	9-10	
Nitrogen content (N2)	%	1	
Plant capacity	MW	660	Gross Output
Stack Height	meter	100, 150, 180	Multiple simulations
Inner Diameter of stack	meter	6.67	-
Flue Gas Temperature	Kelvin (K)	343.15	Without FGD
Flue Gas Temperature	Kelvin (K)	413.15	With FGD
Emission rate/Exit velocity of flue gas/pollutants	Meter/second (m/sec)	21	-

2.1 Measurement of background concentration of air pollutants

Background quantities of NO_2, SO_2, $PM_{2.5}$ and PM_{10} were measured within the five (05) kilometer radius of the power plant. Duration of measurement for each pollutant was once every 24-hours interval for 30-days. Background air quality analysis was performed according to the procedures stated by the Title 40, U.S. Code of Federal Regulations (CFR) as listed in Table 1. Meteorological data such as wind speed and direction, ambient air temperature and humidity was obtained from Meteorological Department of Pakistan.

2.2 Air dispersion modelling

AERMOD View dispersion model (Version 8.2) was employed to evaluate the pollutant dispersion. Air dispersion based on planetary boundary layer turbulence structure and scaling concepts is incorporated into the AERMOD. This model covers both surface and elevated sources for both simple and complex terrain up to a 50 km radius around the modeling source [31]. AERMET View (Version 8.2) was used to pre-process and organize the meteorological data to be suitable for the AERMOD dispersion model. The Turner's method and solar isolation were used to determine the hourly Pasquill–Gifford Stability Classes [32]. Hourly mixing heights data for use in dispersion modelling was interpolated from the morning and evening radiosonde data. The table 2 provides data related to emission sources from coal fired power plant.

To assess the maximum ground-level dispersions of air pollutants a wide-ranging cartesian receptor grid (5 km × 5 km domain) outspreading to 5 km from the center of the pollution source was utilized in the AERMOD modelling. The model was simulated using 100, 150, and 180-meter stack heights. Twelve receptors (human population centers) located within five (05) kilometer radius of the coal power plant were selected as the domain of model.

2.3 Assessment of health risk

Health risk assessment (HRA) of air pollutants; SO_2 and $PM_{2.5}$ was performed according to the procedures laid by National Research Council, Commission of the European Communities and Thoeye et al [33-34].

2.3.1 Hazard identification

Hazards identification involves the verdict of hazardous chemicals present in the environment having the probability to cause adverse effects on health of human. Major chemicals released from conventional coal fired power plants include SO_2, NO_2 and Particulate Matter (PM_{10} and $PM_{2.5}$). Trace elements such as Pb, Hg, Cd, As, Ni, Cr, Sb, and Se has also been reported from many coal power plants in the world [35]. For this study health risks from two hazards (SO_2 and $PM_{2.5}$) have been calculated.

2.3.2 Dose Response

Dose–response refers to the assessment of connection between the pollutant dose and the occurrence of health consequence [36]. Generally, there exists a direct relationship between the pollutant dose and response. In most cases response does not appear at low doses. Start of a response at a dose of the contaminant is mainly dependent on nature of contaminant and its rout of exposure. Dose response relationship is usually characterized by toxicological parameters of reference concentration (RfC) also called reference dose (RfD) in mg kg^{-1} body weight day^{-1}). The RfD is an estimation of the per day oral exposure of a contaminant without noticeable harmful effect during lifetime of a human whereas, RfC is the acceptable everyday concentration of a contaminant in the air [35, 36]. For this study the RfCs have been adopted from National Environmental Quality Standards (NEQS) and the air quality standards of World Bank (WB) and World Health Organization (WHO).

2.3.3 Assessment of Exposure

Exposure assessment is the assessment of quantity of a toxicant exposed to human population or environment. It involves determining the emission pathways and movements of contaminants. During this study we used the air dispersal model to estimate the human exposure of SO_2 and $PM_{2.5}$ released from studied coal power plant. With the help of dispersion model, 24-hour and annual average ground level concentrations of these pollutants were determined within five-kilometer radius of the coal fired power plant.

2.3.4 Risk Characterization

Risk characterization is to quantify the likelihood of adverse health impacts arising from the contact to a contaminant. Risk characterization for this study was done by computing the hazard quotient (HQ) of the SO_2 and $PM_{2.5}$ according to following relationship [37].

$$HQ = EC \setminus RfC \tag{1}$$

where, EC is the exposed air concentration of the pollutant ($\mu g/m^3$) and RfC is the reference concentration of that pollutant in the air ($\mu g/m^3$).

A value of HQ < 1 is considered safe indicating that pollutant concentration in the air is less than the reference concentration whereas, HQ > 1 indicates the existence of potential health risk.

3. RESULTS AND DISCUSSIONS

Background concentration of the pollutants (SO_2, NO_2, $PM_{2.5}$ and PM_{10}) were determined at 12 different locations/receptors within the five km radius of studied coal power plant. Table 3 provides the average concentrations and weighted mean values of the selected air pollutants at each location.

As revealed in Fig 3, the average background concentration of PM_{10} (58 µg/m^3) is slightly higher than the annual reference limit of WB/WHO (50 µg/m^3). It is also noted from Fig 3 that background concentration of $PM_{2.5}$ is significantly higher than the acceptable annual limit value of NEQS (15 µg/m^3) and WB/WHO (10 µg/m^3). Again, this increase may because of the existing industries and road traffic in the area.

Average wind speed in the power plant area is about 4.89 km/h (1.35 m/s) with the maximum and minimum wind speeds of about 8.26 km/h (2.29 m/s) and 1.52 km/h (0.42 m/s) respectively. Direction of the wind in power plant area during most of the time is towards north and south and occasionally towards the North-East (NE) and South-West (SW).

3.1 Air Dispersion modeling results

Air dispersion modeling was undertaken to evaluate the 24-hour and annual average ground level concentrations (GLC) of SO_2, NO_2, PM_{10} and $PM_{2.5}$ within 5 km radius of the power plant considering 100. 150 and 180 m stack heights and the results are provided for 180 m stack height. The model predicts that at 180 m stack height the maximum 24 hourly and annual average GLC of SO_2 is 65.64 µg/m^3 and 8.07 µg/m^3 respectively at 3-5 km downwind from the power plant (Fig 4 & 5). The dispersion of SO_2 in air shed of the power plant is much lower than the NEQS (120 µg/m^3 for 24-hr average & 80 µg/m^3 for annual average).

Figs 2 and 3 respectively provide a comparison of background pollutant concentration with the 24 hourly and annual limit values of National Environmental Quality Standards (NEQS) and the air quality standards of World Bank (WB) and World Health Organization (WHO). As noticed from Fig 2, the average background concentrations of the selected air pollutants in the power plant area except for $PM_{2.5}$ are within the 24-hourly acceptable limits of the NEQS and WB/WHO. The background concentration of $PM_{2.5}$ (28.66 µg/m^3) is slightly higher than the 24-hourly acceptable limit value of WB/WHO (20 µg/m^3). This may because of the existing industries and road traffic in the area.

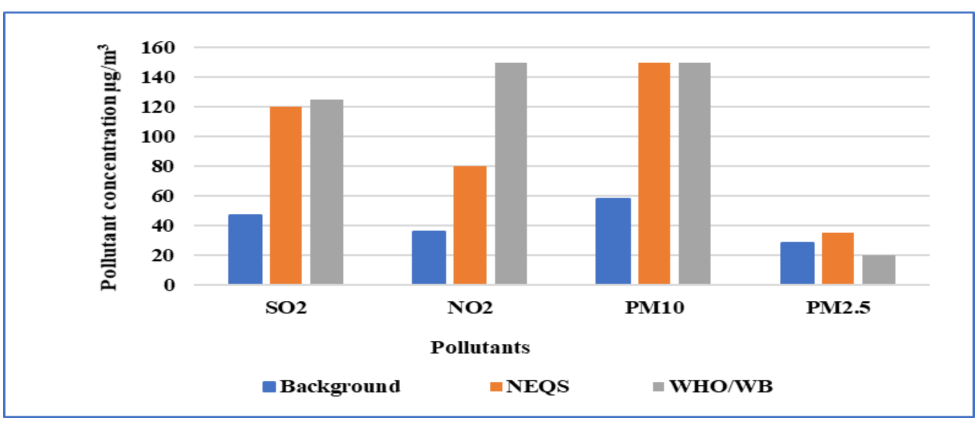

Fig. 2. Comparison of background pollutant concentrations with 24 hourly acceptable limits of national environmental quality standards (NEQS), World Bank (WB) and World Health Organization (WHO).

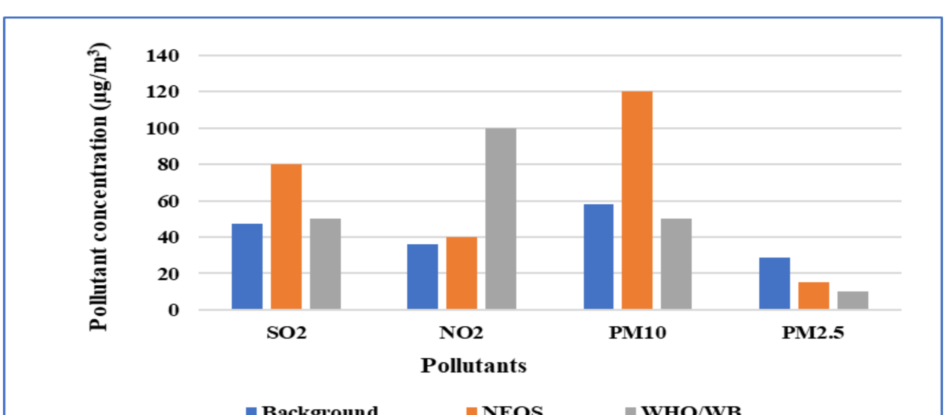

Fig. 3. Comparison of background pollutant concentrations with annual acceptable limits of National environmental quality standards (NEQS), World Bank (WB) and World Health Organization (WHO).

Table 3. Background concentration of air pollutants in the area of coal-based power plant

Location	Pollutant concentrations (µg/m3)			
	SO_2	NO_2	PM_{10}	$PM_{2.5}$
1	39.24	29.63	56.00	22.00
2	41.53	36.75	59.00	28.00
3	44.70	31.17	44.00	29.00
4	43.05	34.42	68.00	31.00
5	46.89	39.58	57.00	32.00
6	45.93	36.08	55.00	25.00
7	47.46	33.75	61	32
8	40.47	29.50	55.00	25.00
9	51.50	40.12	57.00	32.00
10	52.77	39.76	59.00	30.00
11	55.75	38.88	64.00	28.00
12	57.98	41.51	61.00	30.00
Weighted mean	47.27	35.93	58.00	28.66

As shown in Figs 6 & 7, the 24 hour and annual average GLC of NO_2 is 29.95 µg/m^3 and 3.68 µg/m^3 respectively at 3-5 km downwind from the power plant. The dispersion of NO_2 concentration is also much lower than the acceptable limit of NEQS (80 µg/m^3 for 24-hr average & 40 µg/m^3 for annual average).

The maximum 24 hourly average GLC of $PM_{2.5}$ and PM_{10} is 0.66 µg/m^3 and 1.07 µg/m^3 respectively at 3-5 km downwind from the power plant (Figs 8 & 9). The dispersion of PM_{10} and $PM_{2.5}$ in the power plant area is also found much lower than the acceptable limits of the NEQS (150 and 35 µg/m^3 respectively for PM_{10} and $PM_{2.5}$).

The incremental concentrations of the selected air pollutants within five-kilometer radius of the coal power plant were calculated by adding the GLC of the pollutants obtained from air dispersion model and background pollutant concentrations at the stack heights of 100, 150 and 180 m and the average values are provided in Table 4.

As can be noted from Table 4, at 100 and 150 m stack heights, the 24-hourly average incremental concentration of SO_2 (159.75 and 125.06 µg/m³ respectively) surpasses the NEQS limit value of this pollutant whereas, the annual average incremental concentration of SO_2 at all three stack heights is fairly within the acceptable limit value of the NEQS (80 µg/m³).

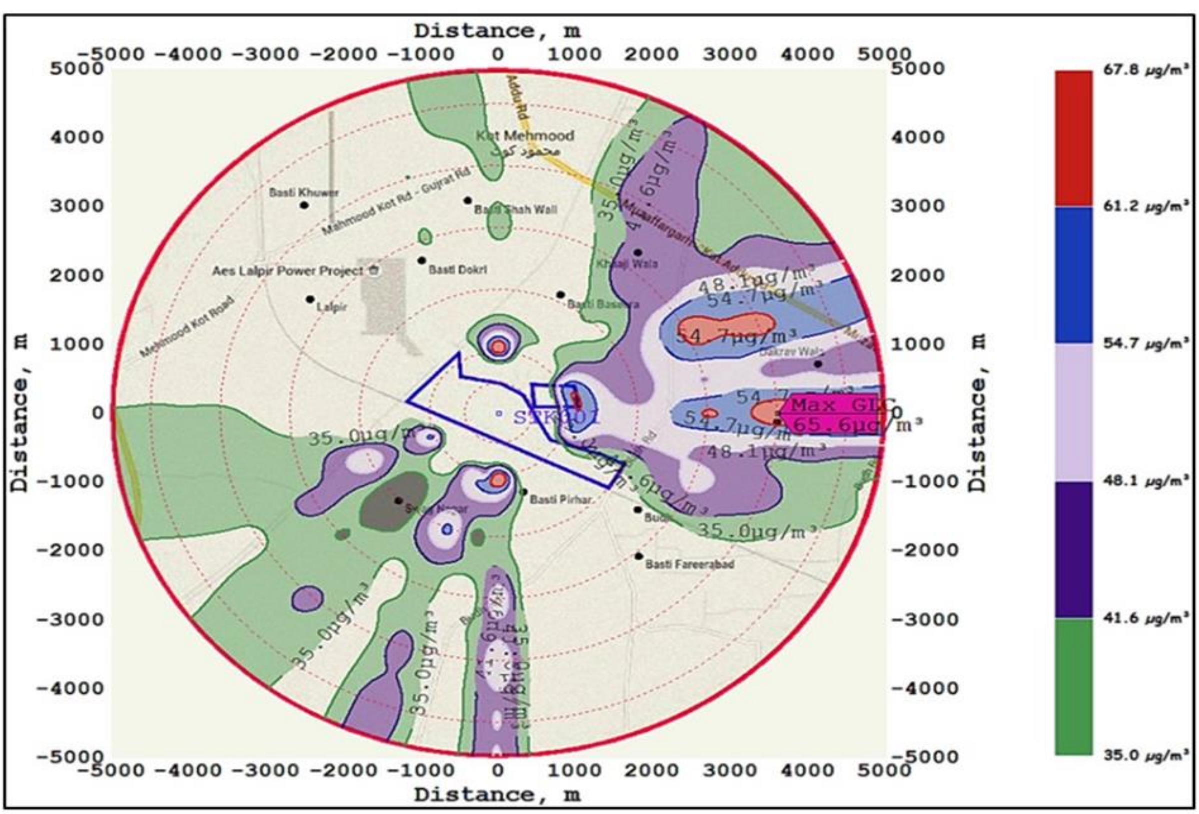

Fig. 4. 24 hours ground level concentration of SO2 at 180-meter stack height.

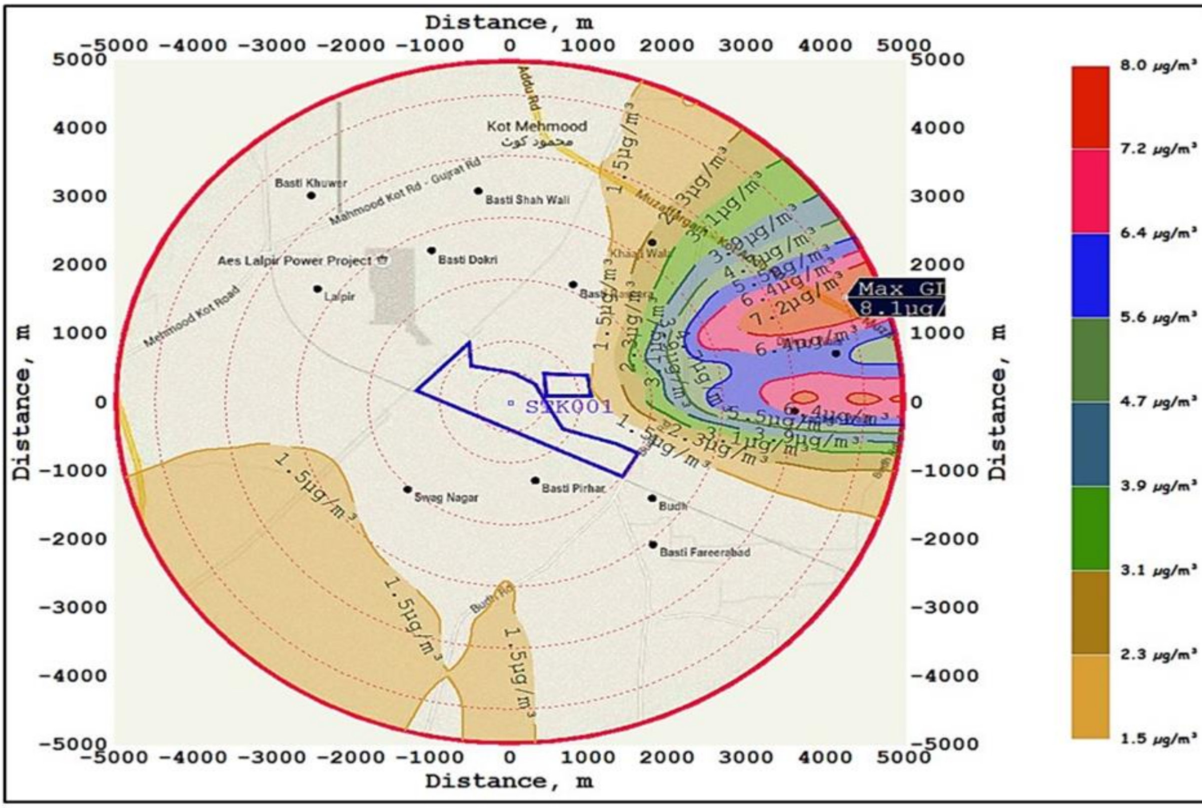

Fig. 5. Annual ground level concentration of SO2 at 180-meter stack height.

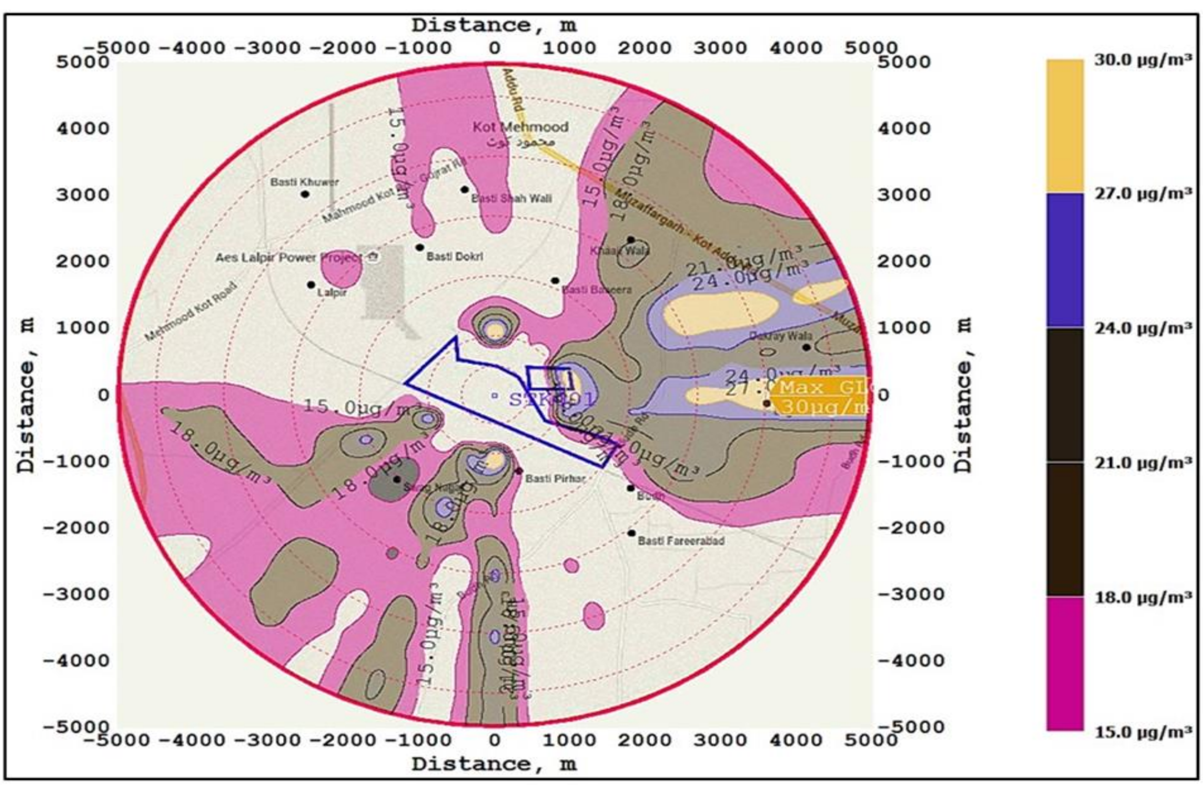

Fig. 6. 24 hours ground level concentration of NO2 at 180-meter stack height.

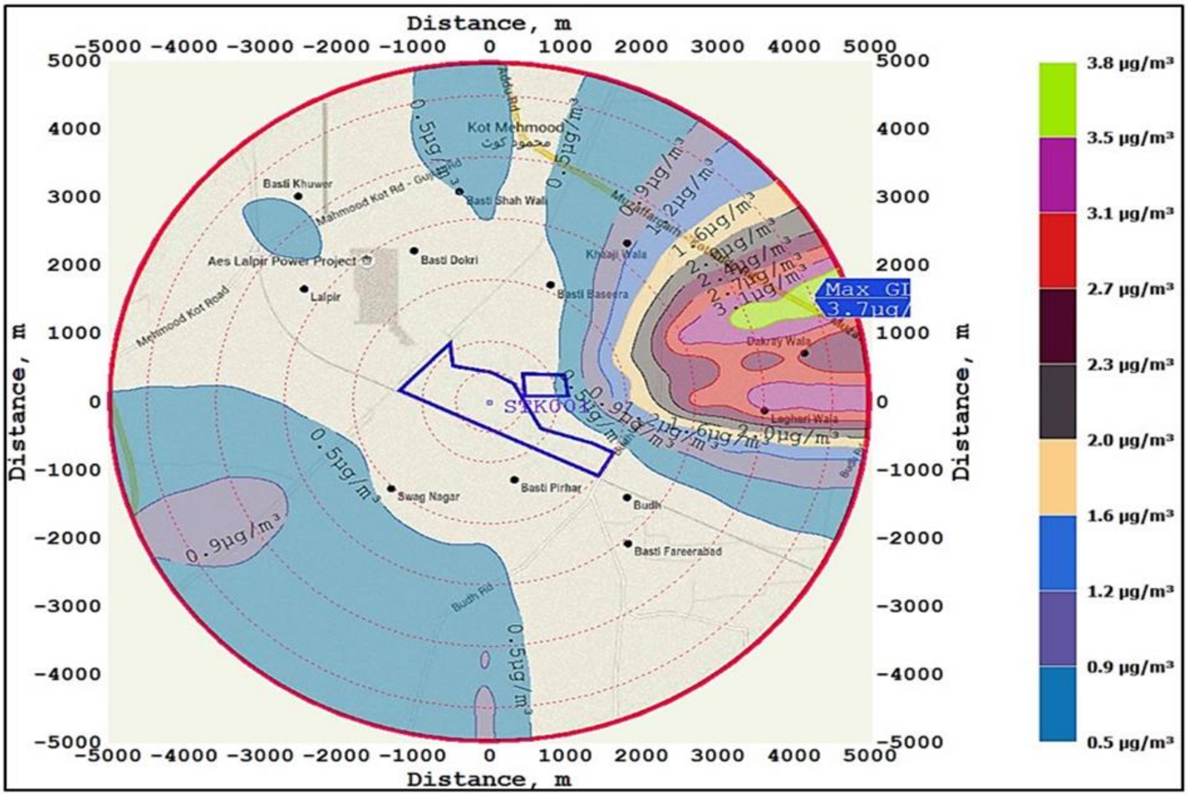

Fig. 7. Annual ground level concentration of NO2 at 180-meter stack height.

The 24-hourly average concentration of NO_2 at 150 and 180 m stack height is within the NEQS limit of 80 µg/m³ for NO_2 while at 100 m stack height the concentration of NO_2 (87.26 µg/m³) is higher than the NEQS value. However, the annual average concentration of this pollutant surpasses the NEQS only at stack height of 100 m as shown in table 4. The modeling results also show that 24 hourly and annual average incremental concentrations of PM_{10} at all three stack heights are fairly within the acceptable limits of NEQS (150 µg/m³).

The 24-hourly average concentration of $PM_{2.5}$ from coal power plant is also found within the NEQS limits however, the annual incremental concentration of $PM_{2.5}$ is higher than NEQS (15 µg/m³) at all three stack heights.

3.2 Health Risk

As shown in Table 5, at all stack heights, a potential health risk exists for 24-hour dispersion of SO_2 (HQ > 1). However, the annual average concentration of SO_2 shows the acceptable level at stack heights of 150 and 180 m (HQ = 1 and 0.90 respectively). At three stack heights, 24 hourly and annual average dispersion of $PM_{2.5}$ poses a potential health risk (HQ > 1) to the human population residing within the 5 km radius of the studied power plant. However, at stack height 180 m, HQ of $PM_{2.5}$ (1.46) is slightly less compared to the values of HQ at 150 m and 100 m (1.47 and 1.48 respectively).

To avoid the health risk from SO_2, stack height of the power plant should be kept equal to or greater than 180 m and suitable sulphur control device such as Fluidized Gas Desulphurization (FGD) be installed. For $PM_{2.5}$ control, this study recommends a stack height of more than 180 m and installation of electrostatic precipitator (ESP). Electrostatic precipitator can reduce about 80-90% of particulate released from the power plant.

4. CONCLUSIONS

Results of this study conclude that stack height is an important parameter of concern while establishing the coal based electric power plants. At 100,150- and 180-meter stack heights a significant difference has been noticed in the annual and 24-hourly concentrations of the NO_2, SO_2, $PM_{2.5}$ and PM_{10} within the five-kilometer radius of the power plant.

According to the findings of this study the 24-hourly average incremental concentration of SO_2 at 100 m (159.75) and 150 m (125.06 µg/m³) surpasses the NEQS limit value of 120 ug/m^3 whereas, the annual incremental concentration of SO_2 at all stack heights is found within the NEQS limit. The 24 hourly and annual average concentrations of NO_2 at 100 m stack height (87.26 and 45.23 µg/m³) is higher than NEQS (80 µg/m³) whereas, at stack heights of 150 and 180 m the incremental concentration of NO_2 is within the NEQS limits for this pollutant.

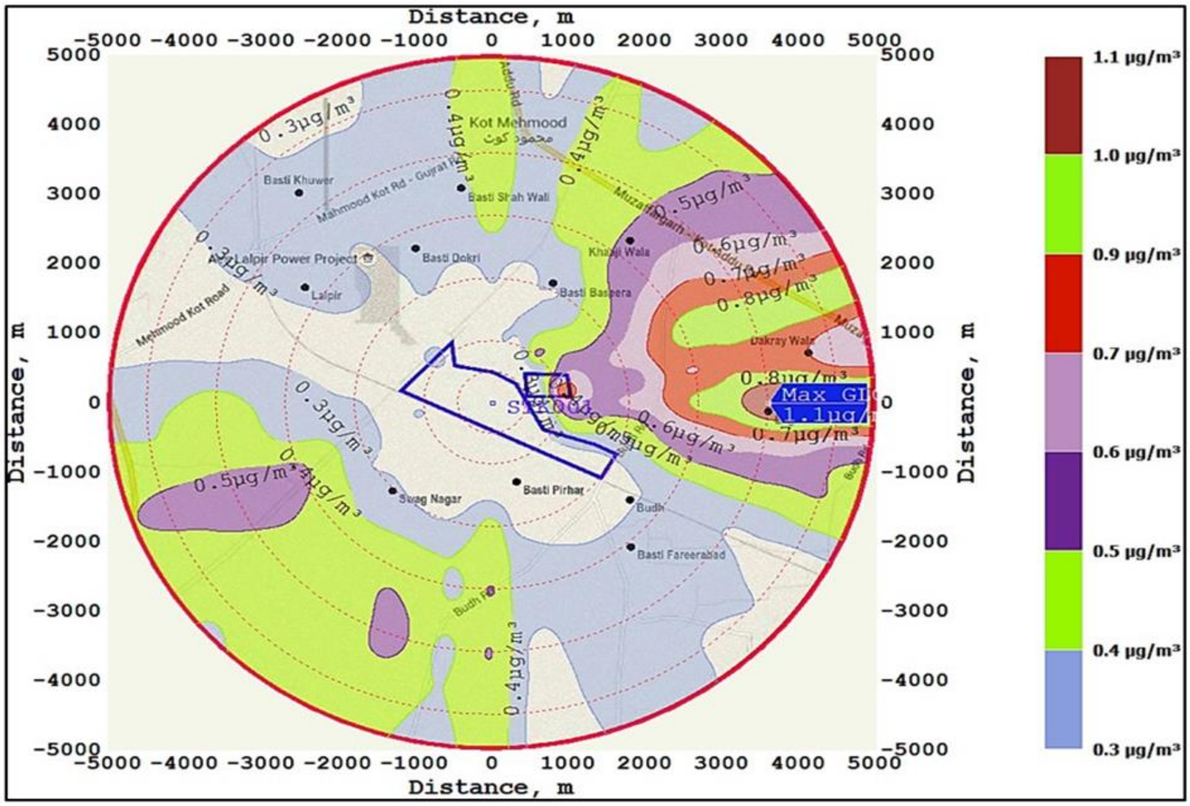

Fig. 8. 24 hours ground level concentration of PM10 at 180-meter stack height.

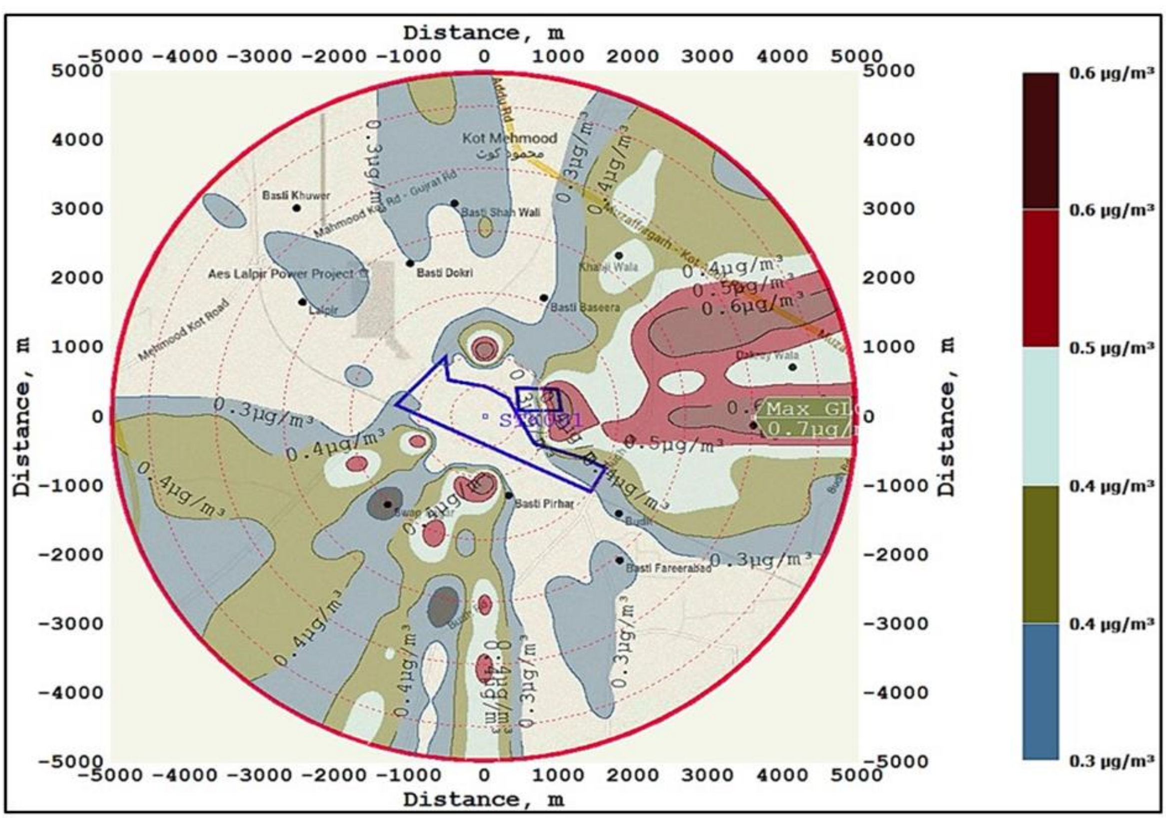

Fig. 9. 24 hours ground level concentration of PM2.5 at 180-meter stack height.

Table 4. Predicted Increment in Pollutants Concentration for multiple Stack Heights

Stack height (m)	Pollutant	Background concentration (μg/m3)	GLC caused by the coal power plant (μg/m3)		GLC + Background Concentrations (μg/m3)	
			Annual	24-hr	Annual	24-hr
100	SO_2	47.27	20.39	112.48	67.66	159.75
	NO_2	35.93	9.3	51.33	45.23	87.26
	PM_{10}	58.00	0.41	1.78	58.41	59.78
	$PM_{2.5}$	28.66	0.2	1.12	28.86	29.78
150	SO_2	47.27	10.72	77.79	57.99	125.06
	NO_2	35.93	4.89	35.5	40.82	71.43
	PM_{10}	58.00	0.21	1.22	58.21	59.22
	$PM_{2.5}$	28.66	0.11	0.78	28.77	29.44
180	SO_2	47.27	8.07	65.64	55.34	112.91
	NO_2	35.93	3.68	29.95	39.61	65.88
	PM_{10}	58.00	0.16	1.07	58.16	59.07
	$PM_{2.5}$	28.66	0.08	0.66	28.74	29.32

Table 5. Health impact assessment of the pollutants released from coal power plant

Stack Height (m)	Pollutant	Predicted ambient air exposure (EC) (μg/m^3)		Reference concentration (RfC)a (μg/m^3)		Hazard Quotient (HQ)	
		24 hours	Annual	24 hours	Annual	24 hours	Annual
100	SO_2	67.66	159.75	50	125	1.35	1.26
	$PM_{2.5}$	28.86	29.78	10	20	2.88	1.48
150	SO_2	57.99	125.06	50	125	1.2	1.00
	$PM_{2.5}$	28.77	29.44	10	20	2.87	1.47
180	SO_2	55.34	112.91	50	125	1.10	0.90
	$PM_{2.5}$	28.74	29.32	10	20	2.87	1.46

[a] World Health Organization (WHO)

The 24 hourly and annual average incremental concentrations of PM_{10} at all three stack heights are fairly within the acceptable limits of NEQS (150 μg/m³). The 24-hourly average concentration of $PM_{2.5}$ from coal power plant is also found within the NEQS limits however, the annual incremental concentration of $PM_{2.5}$ is higher than NEQS (15 μg/m³) at all three stack heights

Study also concludes that stack height of the power plant has reasonable correlation with the human health. Although at all stack heights, a potential health risk exists for 24-hour dispersion of SO_2 (HQ > 1) however, the annual concentration of SO_2 shows the acceptable level of health risk at stack heights of 150 and 180 m (HQ = 1 and 0.90 respectively). The 24 hourly and annual average dispersion of $PM_{2.5}$ at all stack heights also poses a potential health risk (HQ > 1). Overall this study recommends a stack height equal to or greater than 180 m to minimize the potential environmental and health risk from air pollutants in the locality of coal fired power plant.

The key implication of this study is that although the environmental pollution and health hazard from a coal-based power plant can be controlled by adjusting the stack heights, however this should not be considered a final solution of the problem. There is always a need to install the appropriate pollution controller devices such as Flue Gas Desulphurization (FGD), Electrostatic Precipitators (ESP) and scrubbers etc. to control sulphur and particulates released from the power plant which otherwise can have serious environmental and health issues in the close vicinities of the power plant. Further it is worth noting that due to their far-reaching health risks and impacts on environment and climate, currently the coal power plants are considered a least favorable option for power generation. Globally and including Pakistan a policy shift can be witnessed in the energy mix from nonrenewable to renewable sources such as wind, hydro and solar.

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