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Holistic and Scientific Perspectives of Energy Sector in Pakistan: Progression, Challenges and Opportunities

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ABSTRACT In the modern era of high-tech machines and advanced technologies, Pakistan yet fails to mitigate its daunting energy crisis and power shortage of 2765 *MW* presently, which eventually affects the economy and well-being of the nation. This article highlights and discusses the key issues in the energy sector of Pakistan and how they give rise to the load shedding, tariff rates and environmental damage subsequently. Unfortunately, the country has the highest power production share of 63.9% from thermal power plants and least of about $5-6\%$ from renewable sources. In contrast to renewable sources, the thermal power generation being exhaustible has many drawbacks such as rapid depletion of fossil fuel reserves, inevitable varying costs, shorter life expectancy and most notably the undesirable environmental impacts. In addition to all this, the transmission and distribution networks need to be upgraded to uplift the current carrying capacity of utility network otherwise may lead to the aging of system equipment, overloading of power and distribution transformers, increasing of power losses and many other factors contributing to the energy and economic concerns in the country. In the view of strategic analysis and detailed study made on the energy sector statistics, it is evident that Pakistan has promising potential of renewable energy resources especially solar, wind, and hydel to overcome the energy, economic and ecological problems in the country particularly and the region as a whole.

INDEX TERMS Power sector, energy mix, energy crisis, sustainable energy resources, line losses.

I. INTRODUCTION

In today's world, electricity has become an integral part of our life, starting from dawn with cooking breakfast to dusk on listening news. All the appliances in our daily life activities majorly rely upon the availability of electrical energy and its shortage results in discomfort and unpleasant lifestyle. The energy crisis is still a critical issue including supply-demand gap [1], load shedding, high technical and non-technical losses. Looking at the current scenario of electrical energy in Pakistan, it is necessary to analyze its four major sections i.e. generation, transmission, distribution, and utilization independently, as shown in Fig. 1. Each of these entities has its own role. As for generation, the fuels including natural resources are the *starting point* for the generation cycle, whereas the transmission network links the power production to the distribution system and the distribution system is responsible for distributing power to the end-users. Apart from such basic components of the power system, the monitoring and controlling devices are equally important for maintaining the reliability, quality, and security of power being distributed and utilized [2], [3]. Further, the proper placement and coordination of protection devices is also a crucial aspect for avoiding unnecessary power outages and mitigating the contingencies at initial stages before they get worse by the time [4], [5].

The power system of Pakistan however uses conventional energy resources for power generation like thermal energy using fossil fuels but still faces a severe energy crisis while the country is blessed with enormous renewable energy potential. Since the irreversible nature of fossil fuels like crude oil, coal, and natural gas leads to various problems such

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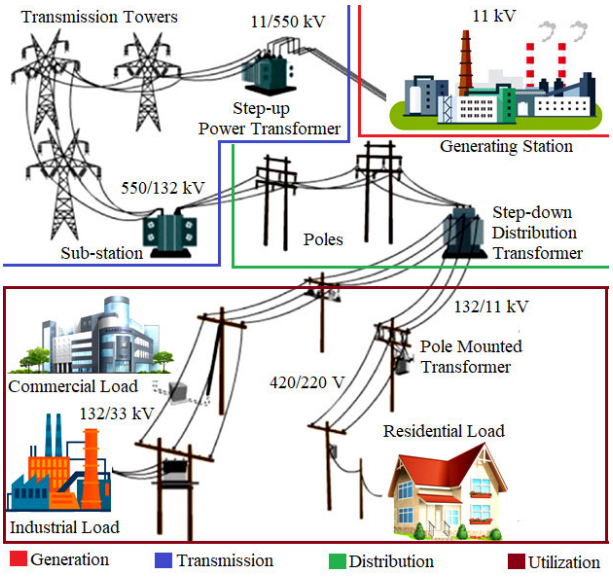


FIGURE 1. General representation of electric power system in Pakistan.

as environmental issues like CO_2 emissions, the greenhouse effect, global warming, and uneven weather patterns [6], [7], loss of economy and increasing tariff rates [8], [9]. Mostly, these fossil fuel-based thermal power plants have expensive generation due to an increase in oil prices and financial complications for the government to pay for it. Meanwhile, the electricity sector of Pakistan has started to fall into an economic crisis, and eventually, the gap between supply and demand is still in a range between 2000 to 3000 *MW* [10], [11]. This gap has been affecting the consumers by intentionally disconnecting their loads from supply **load shedding** to maintain the energy balance, which has become a common problem [12], [13] these days all over the country. The major reasons behind the deficiency of electricity sectors are; inadequate installed generation capacity, obsolete power plants, incapable transmission and distribution systems, outdated infrastructure and poor financial management [14], [15].

Due to increasing electricity demand, discouraging energy market scenarios, rising transmission and distribution losses, and growing overloading issues, the utility network has gained more attention, which is operated vigorously under heavily loaded conditions [16]. To better understand the trend of losses occurring at various stages and to alleviate them, it is important to analyze the respective load profiles. However, most of the losses exist in transmission and distribution networks and they make up the single largest consumption or ingestion in the power system. The losses above 16% indicate that there is an existence of inclusive line tampering and frequency above 40% raises economic and social concerns for the country. Unfortunately, the losses in the transmission and distribution networks are more than the nominal value, as compared to any other neighboring country. This is due to the fact that existing electrical infrastructure is not being upgraded for decades, causing unnecessary and unavoidable technical and non-technical losses [17], [18]. The technical losses, being dependent on physical properties of the material i.e, its resistance, cause power dissipation in the distribution lines and transformers. Such losses can be easily simulated and calculated using different tools and techniques [19], [20]. On the other hand, the non-technical losses are: loose connections, deficiencies in the energy measurement processes, errors in readings and recordings, pseudo in meters, electricity theft, poor maintenance, accounting mistakes, and many other factors [17], [21]. The financial load brought by these losses thus pushes the authorities to subsidize the energy tariff for the consumers [22], which further presses the economy down.

Fortunately, with the enormous potential of sustainable energy resources in the country, especially solar, wind and biomass [23]–[25], it's desirable to utilize them effectively to deal with rising energy demand, owing to their non-exhaustible characteristics and environmental-friendly nature [26]–[29]. Further, the transmission and distribution networks also need due attention, because no matter how much the generation capacity is going to increase but if the supply network is weak, the system will collapse at the end. Therefore, the scientific community in the country should be encouraged to conduct and carry out the experimental evaluations of transmission and distribution losses, aging of system equipment, and overloading of transformers and feeders at laboratory levels such that the effective and efficient networks can be retrofitted.

To the best of our knowledge, there are no such comprehensive surveys being made already on the energy sector in Pakistan that discuss and analyze its holistic and scientific perspectives altogether. The major contributions of this work are **(1)** to investigate and report the historical and current progress of the energy sector in Pakistan on the basis of statistical data and personnel survey **(2)** to layout the detailed description of generation, transmission and distribution sectors of Pakistan and highlight the major energy actors and their key roles **(3)** to propose the remedial actions and possible techniques to overcome the adverse effects on the energy, economy, ecology, and well-being of the country. The rest of the article is organized as follows: section-II discusses the national energy mix including renewable and non-renewable energy sources. Section-III examines the consumption pattern and supply/demand deficit. Section-IV analyses the potential of renewable energy resources like wind, hydel, biomass, and solar in the country. Section-V evaluates the transmission and distribution networks based on power losses, overloading status, and aging of system equipment. Section-VI highlights the major issues in all energy sectors. Section-VII suggests promising solutions for energy and economic issues and finally, Section-VIII gives final conclusive remarks.

II. ENERGY MIX

Electrical energy has an important role especially in developing contemporary economies. It is also the basic pillar of the

economic growth in Pakistan, due to the close relationship between energy demand and economic development share [30], [31]. Having such a positive correlation, the power shortage adversely affects the GDP rate, due to the loss in productivity of goods and services. Therefore, it is required to prioritize all the power and energy sectors, so as to improve not only the economic growth of the country but also the well-being of individuals. However, it's a challenging task for a single entity i.e, the ministry of energy and power (MOEP) to look-after all the power and energy sectors and thus necessitates to frame-out a hierarchy to regulate and monitor the performance, operation, and security of the entire networks [32]. Further, it is desirable to have multiple energy providers to avoid market bias and monopoly and also to make sure that the electricity is being supplied to end-users easily and reliably.

With the rising population in the country as being reported by World Bank [33], which is increasing at 2% per year shown in Fig. 2, the need for electricity increases in all the sectors i.e, residential, commercial, agricultural, municipal, industrial, etc. The industry 4.0 revolution encourages to promote automation of existing as well as new industries, which itself eventually results in increased energy demand [34], [35]. With growing energy demand, if the responsible authorities do not retrofit new power plants and if the energy gap widens, it will ultimately cause system instability and in the worst situation a complete blackout.

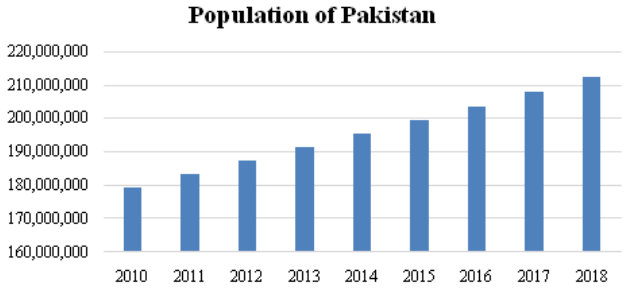


FIGURE 2. Trend of population growth in Pakistan between 2010 and 2018 [33]. The data indicates approximately a 2% growth rate per year.

Therefore, it is necessary to analyze the existing energy system and plan for the future, based on the load forecasting and power flow studies. The following subsections discuss the existing installed capacity of the country and its potentials on generating more using different energy sources, without violating the international norms and standards.

A. INSTALLED CAPACITY

Instead of having power generated from diverse energy sources in the country, yet most of it is from conventional resources with cumulative contributions from different private and public energy actors including WAPDA, GENCOS, IPPs, and K-Electric. The fuels commonly exploited for electricity generation in the country are nuclear, thermal, hydel, wind, solar, and bagasse, which all made-up to an installed capacity of 35372 *MW* during 2017 − 18. Out of which, 32525 *MW* and 2847 *MW* are from PEPCO and K-Electric respectively using different energy sources with the corresponding share of 120754 *GWh* and 13072 *GWh* [36]. The energy mix of the country using different sources for power production is shown in Fig. 3 [37].

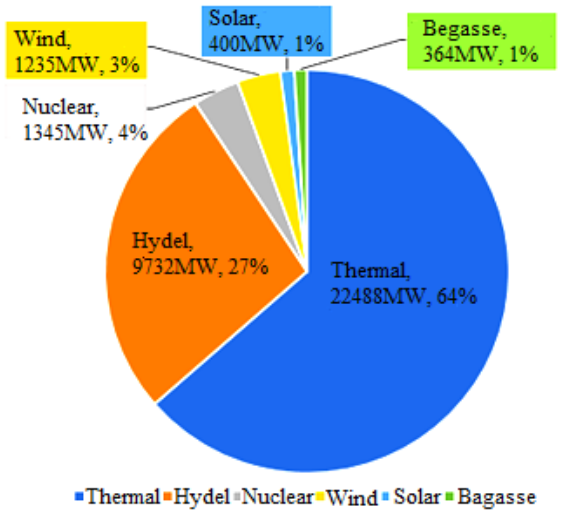


FIGURE 3. Energy mix of Pakistan for power production [37]. The country has major share of thermal generation with least focus on renewable sources i.e, wind, solar and bio-mass.

It can be seen in Fig. 3 that the thermal generation marks its major share in power production followed by hydel, nuclear, wind, solar, and bagasse. Such a trend with the least contribution and utilization of renewable sources is quite alarming considering the over-dependence on oil which eventually results in, not only circular debit but ecological depreciation as well.

B. THERMAL POWER GENERATION

Unfortunately, the country having large coal reservoirs, is exploiting other imported and local fossil fuels such as; natural gas, furnace oil, and high-speed diesel for power production. Pakistan has large coal mines in Sindh province, which if utilized efficiently and properly will mitigate the daunting energy crisis in the country. The government is, however, taking initiatives to make the most of it and has started a partnership with China for the erection of new coal-fired power stations all around the country. Moreover, oil import especially for power production is one of the core reasons for the rising national debt. Any measure to reduce the current account deficit would require to curtail oil import, which eventually demands to discourage the electricity generation from oil and promote green energy [38].

The share of power produced from various sources such as; RLNG, gas, residual furnace oil, coal, and high-speed diesel includes 22.99%, 32.25%, 30.63%, 13.27%, and 0.86% during the year 2017 − 18 respectively in contrast to 48.58%, 0.83%, 47.08%, 1.34% and 2.16% during 2017 − 18 as shown in Fig. 4. This graph shows a rising trend of gas and coal utilization whereas the opposite for RLNG, furnace oil, and high-speed diesel in the year 2017 − 18.

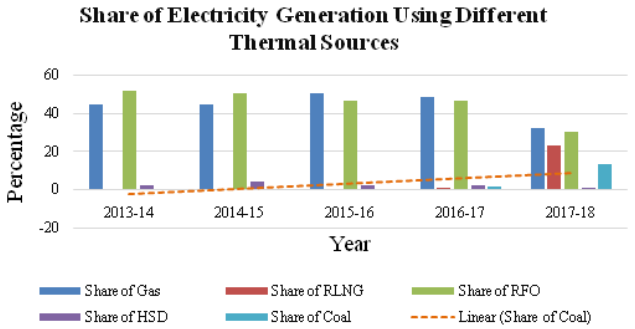


FIGURE 4. Contribution of different fuel sources to the share of thermal power generation in the country.

Further, the historical trend of thermal power generation from GENCOs and IPPs in Fig. 5 shows an increase in installed capacity each year in the duration of 2013 – 2018. However, the consumption of fuels i.e, RLNG and coal for thermal power generation in Fig. 5 is increased by 21173.32 *GWh* and coal 12224 *GWh* each year [39]–[43]. Such sources, however, help to mitigate the energy crisis in the country but eventually results in global warming, land degradation, ocean acidification, etc [44]–[46], which is a frightening situation for the community.

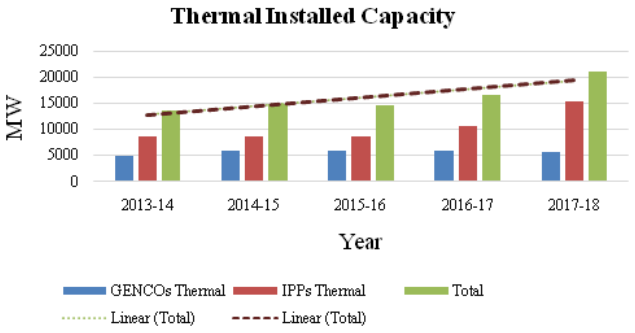


FIGURE 5. Installed generation capacity from thermal power plants.

C. HYDEL POWER GENERATION

Hydropower generation being environmentally friendly, had a significant share of about 8, 713 *MW*, accounting for 24.22% in the installed capacity of the country at the end of FY 2017 – 18. Looking at the historical data, such share during FY 1985 – 86 was around 67%, showing its downwards trend. Similarly, the share of hydro in the energy mix of the country in the same year was 21.00% compared to 26.59% during last year. Most of the existing hydropower plants are installed and operated by WAPDA, whereas only 372 *MW* is contributed by the private sector. In the last year 2019, the positive growth in a hydel generation was observed, constituting 27% which could be even more but due to seasonal changes were restricted. This means that, for this type of power generation, it is mandatory to maintain the level of the water reservoir and its inward-outward flows, controlling not only flooding situations but also to fulfill the needs of agricultural fields in the country. The comparative study made

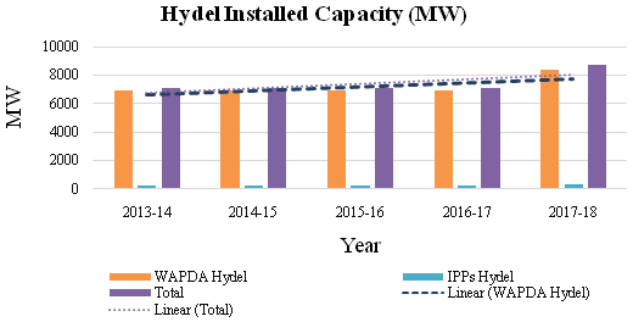


FIGURE 6. Installed capacity of hydro power stations in the country.

in Fig. 6 illustrates that contribution of hydropower generation in the duration from 2013 – 14 to 2016 – 17 was consistent and shows positive drift in the year 2017 – 18 [39]–[43].

D. RENEWABLE ENERGY GENERATION

Pakistan however has many renewable energy sources but the existing power generation from them only includes wind, solar, and bagasse, as shown in Fig. 7. In the FY 2014 – 15, the total installed capacity of wind power generation connected to NTDC's system was 256 *MW*, compared to 106 *MW* during FY 2013 – 14, due to the installation of three new wind-based power plants (FWEL-I, FWEL-II, and TGF) having capacity of 50 *MW* each. Looking deeper into the wind energy production, during FY 2014 – 15 it was about 459 GWh against 263 v in FY 2013 – 14. With the rising percentage of wind farms, the cumulative contribution during FY 2017 – 18 reached to 1078 *MW*. In addition to this, three new bagasse-based power plants having a total capacity of 70 *MW* were added into the system during FY 2014 – 15, with corresponding energy production of 308 *GWh*. The capacity of such power plants increased to 301 *MW* in FY 2017 – 18. Further, during FY 2014 – 15, a first mega solar park named Quaid-e-Azam solar power plant with a total capacity of 100 MW was installed into the system having a respective energy contribution of about 28 GWh. This capacity raised to 330 *MW* in FY 2017 – 18 as defined in Fig. 7. It depicts the slowly rising percentage of given renewable energy sources from 2013 to 2018 [39]–[43]. Unfortunately, the renewable

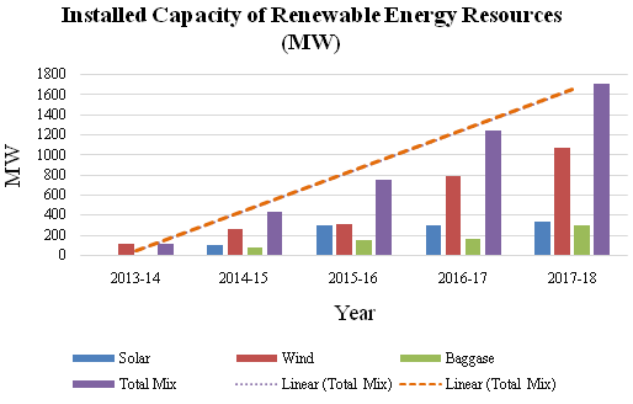


FIGURE 7. Installed capacity of renewable generation in the country.

energy sources only contributes 5 – 6% in the energy mix of the country as shown in Fig. 3.

However presently, thermal generation takes the lead in electricity production with their excessive reliance on Gas and RLNG but luckily during 2019, the share of renewable power generation increased by 1%, which gives hope on its positive trend in coming years as well [47]. Apart from all this, Pakistan has other natural resources i.e, geothermal, tidal, bio-energy, etc that can be integrated commercially to overcome the energy, economic and ecologic issues [26], [27], [48].

E. NUCLEAR POWER GENERATION

Nuclear power generation holds its significance in the energy sector of the country and it is solely being operated, maintained, and monitored by PAEC. The share of nuclear in the energy mix was approximately 5% during FY 2017 – 18 but has been increasing consistently. In the FY 2017 – 18, the nuclear power generation was 1467 *MW*, compared to 1142 *MW*, 787 *MW*, 650 *MW*, and 650 *MW* during 2016–17, 2015–16, 2014–15 and 2013–14 respectively, as illustrated in Fig. 8, showing increasing percentage in consecutive years [39]–[43]. Further, Pakistan aims at increasing its nuclear generation to 8800 *MW* by 2030 with a close partnership of Chinese subsidiaries [49], [50].

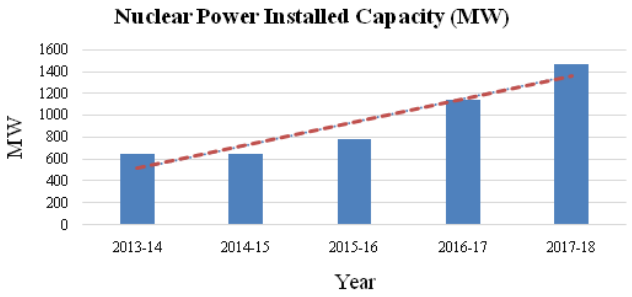


FIGURE 8. Installed capacity of nuclear power plants in the country.

Considering all, it shows the over-dependence of Pakistan on fossil fuels, primarily on oil for meeting its energy demand. But it is also the fact that local and indigenous resources such as; natural gas are also limited and plans are afoot for its import from Iran, Turkmenistan, and Qatar with a joint natural gas pipeline [8], [55]. However, importing fossil fuels, on one hand, has become a serious burden on the national exchequer and on the other hand, creates thoughtful doubts on the energy security of the country. Additionally, the consistently varying fuel prices in the global market and its shipment to Pakistan, which include the zones of serious conflicts, pose a challenge for policymakers in the country as well [15].

III. ENERGY CONSUMPTION AND SURPLUS/DEFICIT

A. CONSUMPTION PATTERN

Looking at the consumption pattern in Fig. 9 [47] for two consecutive years, there is a significant change among different loads. During 2019, the electricity consumption of domestic

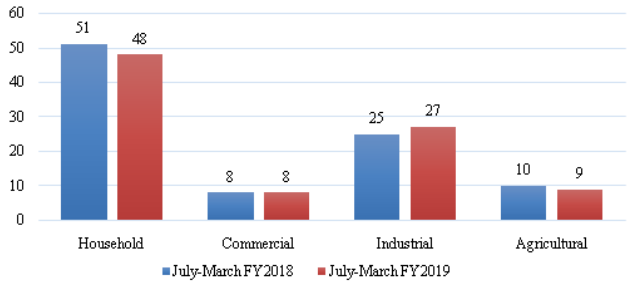


FIGURE 9. Share of different loads into the consumption pattern of electricity.

and agricultural loads was reduced, which is an indication that the individuals were trying to rationalize their consumption because of the increased tariff rate. However, an increase in consumption of the industrial load is a positive sign, evidencing the revival of an industry which was suffering before, due to extensive load-shedding.

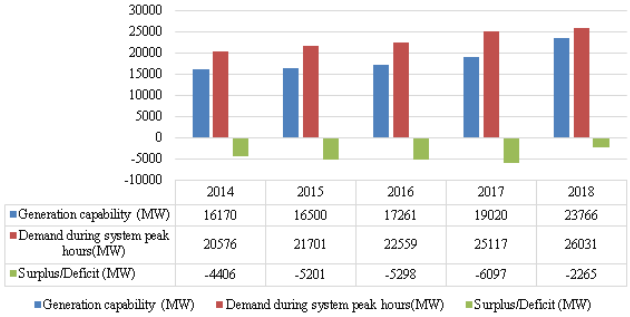
The rising tariff rate due to fluctuating oil prices has a negative impact on consumer products, which eventually results in increased unemployment and inflation rate [57] with the corresponding reduction in real wealth and consumption spending [58]. The high prices also negatively affect investment, interest rate, currency value, and stock prices. To improve the economic growth in the country, it is desirable to frame-out appropriate and profitable policies, to not only regulate energy prices but also to encourage sustainable energy production to meet the increased demand in the country [59]. Further, it is also recommended to promote energy-efficient and cost-effective appliances to save energy [60]–[62].

B. SURPLUS/DEFICIT IN DEMAND AND SUPPLY

Pakistan is giving the highest priority to its energy sector and that can be seen with installed capacity reached to 23766 *MW* at the end of 2019. However, there still exists a considerable energy gap between supply and demand in the country, due to the lack of resource utilization and inefficient system and policies [1]. To understand such energy gap, its profile during peak seasons for NTDC and K-Electric systems is reproduced in Fig. 10 and Fig. 11 respectively [41]–[43]. It is clearly shown in Fig. 10 and Fig. 11, a deficit of 2265 *MW* and 500 *MW* prevails in NTDC and K-Electric systems, due to multiple reasons such as; improper load-forecasting strategies, a high percentage of technical and non-technical losses, undesired aging effects, etc. Therefore, Pakistan, being a consumption-oriented society, needs to take necessary measures to meet its growing energy demand, as discussed in [63].

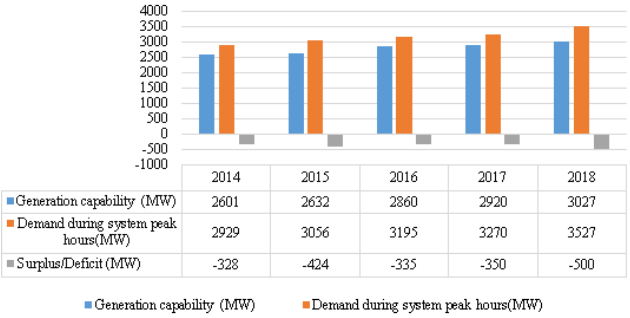
IV. POTENTIAL OF SUSTAINABLE ENERGY RESOURCES

Alike other developing nations, Pakistan is also trying hard to control its energy shortfall and improve its payment balance. Pakistan is already giving importance to its natural non-conventional sources i.e, wind energy, solar energy, geothermal, tidal energy, bioenergy, micro/small-hydel,



	2014	2015	2016	2017	2018
Generation capability (MW)	16170	16500	17261	19020	23766
Demand during system peak hours(MW)	20576	21701	22559	25117	26031
Surplus/Deficit (MW)	-4406	-5201	-5298	-6097	-2265

FIGURE 10. Supply-demand profile during peak hours with surplus/deficit of energy marked in the NTDC system.



	2014	2015	2016	2017	2018
Generation capability (MW)	2601	2632	2860	2920	3027
Demand during system peak hours(MW)	2929	3056	3195	3270	3527
Surplus/Deficit (MW)	-328	-424	-335	-350	-500

FIGURE 11. Supply-demand profile of K-electric system during peak hours with surplus/deficit of energy marked.

and other emerging technologies like fuel cell that can be integrated commercially to curtail the energy deficiency and eventually the energy crisis. By promoting green energy sources, Pakistan has a great opportunity to attract foreign investments to not only reduce its current account deficit but also improves the energy sector of the country [64]–[66].

A. WIND ENERGY

Wind energy being green and free, has growing interests not only in developing but developed countries as well, viewed as stable, qualitative, durable, reliable, and commercially attractive source [67]–[70]. In order to understand the total potential of wind energy in Pakistan, a mapping exercise was done by the Government of Pakistan in-close collaboration with the World Bank, which resulted in 130, 000 MW as an expected wind generation capacity of the country [71]. Pakistan has a total coastal line of about 1100 Km for wind generation, with the majority of it in Sindh province having a wind corridor of precisely 60 km in width and 180 km in length, capable of generating 50 GW of electricity [72]. Some of the other coastal regions are available in the Baluchistan province and northern areas [43], [73]. The wind speed in most of the coastal belts in the country hits approximately $4 - 9$ m/s and 12.5 m/s at a height of 10 m and 50 m respectively, determined by installed anemometer in the respective wind zones [49], [74].

Referring to a recent survey made by National Renewable Energy Laboratory (NREL) US [75], it is found that Pakistan has tremendous potential of wind power generation equals to around 346 GW. Further, this study analyzed the mean annual wind profile of the country's coastal line for the period $2000 - 2010$ and explored that country has a good wind regime as depicted in Fig. 12 [76]. In addition to this, NREL US also revealed the wind map of country in Fig. 13 at 50 m height with power class, resource potential, power density and speed [77]–[81]. It shows that about 3% of the total land area of the country, which is approximately equal to 26, 400 $sq.$, is capable of generating 132 GW of electricity. As a case study, the Noori-abad site in Pakistan was chosen for economic analysis and found that wind energy is produced at USD $0.02189/kWh$ at a height of 50 m [82].

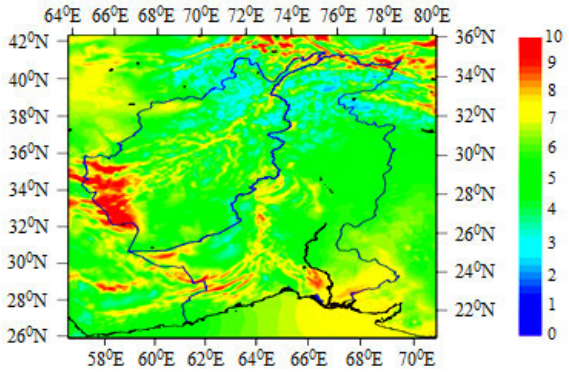


FIGURE 12. Profile of simulated mean annual wind speed at 100m above the ground level [76].

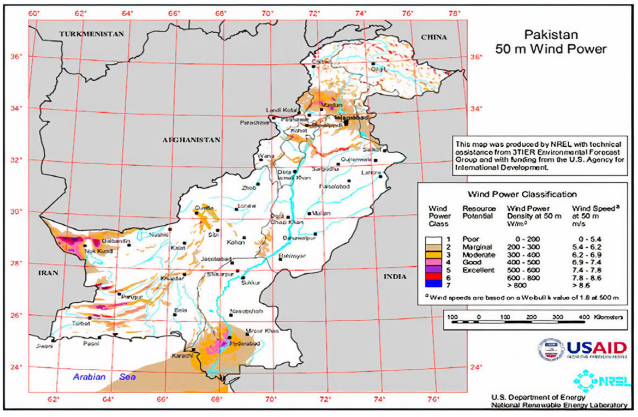


FIGURE 13. Wind potential of different areas in the country being marked [78].

B. SOLAR ENERGY

Solar energy being the most capable and advantageous renewable source is not significantly susceptible to seasonal variations and is the most reliable as well. Pakistan with a solar energy capacity of 2900 GW collects solar irradiance of approximately $1900 - 2200$ kWh/m^2 annually on a global value scale, which is among the finest countries across the world [65], [87]. However, on daily basis, an irradiance of about $5 - 7$ kWh/m^2 occurs in the country [84], [85], occluding more than 95% of its surface area, with a persistence factor of more than 85%, which means that the sun energy of

$18 - 25\ MJ/m^2$ per day is available as a natural input energy resource to PV panels for electricity generation [49], [86]. Moreover, the demand for PV modules is rising at a rate of 30 *to*40%, due to their higher life expectancy and promising performance [84]. With the growing trend of PV technology, it has been predicted that the share of solar power generation into national grid system will reach 11% by 2050 [88], which was 1.2% and 2.8% during 2008 and 2011 respectively [89].

C. BIOMASS ENERGY

Biomass is one of the important energy sources in the energy mix of the country with its increasing share. Since, Pakistan being an agricultural country, accumulates large piles of biomass from farming and livestock sectors in the form of crop residues and animal waste respectively. Such raw biomass can be used as unrefined fuel outside the commercial economy for residential and industrial purposes even. For-example; some of the sugar mills in the country use bagasse for electricity generation to fulfill their demands and have excess cumulative power of about 0.7 GW annually, which can be added to the national grid system [65], [90]. The agricultural waste i.e, corn stalks, cotton stalks, sugarcane trash, wheat straw, and rice straw with corresponding residues of 6.43, 50.6, 8.94, 35.6, and 17.86 Mt, has the potential of generating $4800 - 5600\ MW$ of electricity [91]. Similarly, the electric potential of municipal solid waste by thermo-chemical and biochemical conversion is 560 kWh/t and 220 kWh/t, respectively [92]. Moreover, Pakistan having approximately 50 million animals, the daily waste from them is around 10 kilograms, accounting for 24 million cubic-meters of bio-gas [93]. Such a high potential of biogas can be used in many applications including cooking, lighting, transportation, industry, etc, and is also one of the feasible solutions for electrifying the rural areas, where it is found and can be utilized locally.

D. HYDEL ENERGY

Pakistan has a total hydro generation potential of $60,000\ MW$, with most of it lies in Khyber Pakhtunkhwa ($24,736\ MW$), Gilgit-Baltistan ($21,125\ MW$), Azad Jammu & Kashmir ($6,450MW$) and Punjab ($7,291MW$). About 89% of this hydro-generation capacity is still untapped and yet to be exploited, due to the fact that irrigation network and natural water flow systems in the country are evidence that this potential if harnessed properly, is able to mitigate the energy crisis in Pakistan [81]. Referring to natural water flows in the country, the small hydro-power plants are considered as one of the lucrative choices for electricity generation. At present, 128 MW is already generated using this technology, 877 MW hydro projects are under implementation and around 1500 MW of capacity exists for future developments. Table 1 shows the potential available for the installation of micro/mini-hydro (below 50 MW) stations in Sindh, Punjab, AJK, and the northern mountainous regions of the country [94].

TABLE 1. Potential of small hydro station installed in country at province level.

Area	Potential (MW)	Total Sites	Cumulative Potential (MW)	Type
Sindh	5-40	150	120	Canal Falls
G-B	0.1-38	200	1300	Natural Falls
Pujab	0.2-40	300	560	Canals
KPK	0.2-32	125	750	Natural Falls
A.J.K	0.2-40	40	280	Natural Falls

V. TRANSMISSION AND DISTRIBUTION NETWORKS

The electricity network of Pakistan is built upon the transmission and distribution lines of 500, 220, 132, 66, and 11 kVs, with two entities i.e, NTDC and K-Electric being involved in managing them under the section-17 of NEPRA Act. As of June 2018, NTDC operates and maintains sixteen 500 kV and forty 220 kV Grid stations with $5,772$ Km, 500 kV and $10,753$ Km, 220 kV transmission lines respectively [95]. Further, the construction of an 878 Km long HVDC bi-polar transmission line operating at ± 660 kV is under process and expected to be finished by 2022. Moreover, ten public sector DISCOs and K-Electric has been granted licenses by NEPRA to supply electricity to end-users in their respective areas and suburbs. Additionally, NEPRA has approved nine distribution licenses to SPPs and one to CPP, to supply electricity to designated bulk power customers [43]. The existing transmission and distribution networks suffer from voltage fluctuation, low voltage on the consumer side, and household efficiency losses due to improper management, delayed maintenance, use of inefficient power components, etc [13], [96].

A. TRANSMISSION AND DISTRIBUTION LOSSES

Energy losses are a major concern of utility networks, which occur at different stages in supplying electricity from generation to end-user due to technical and non-technical reasons. Technical losses are highly related to energy dissipation in the conductors whereas non-technical losses are due to theft of electricity [17], [97], [98]. In addition to the costly energy mix, the other key reason for the high tariff rate in the country is the excessive transmission and distribution losses [60], [99].

Unfortunately, theft of electricity is a common problem in most of the regions of the country and costs billions of dollars annually. This problem has technical, socioeconomic, environmental, and political roots and its solution is normally pursued only through efficient administrative work, technical measures, and proper check and balance [100]. These technical and non-technical looses also affect quality of power in transmission and distribution networks [101]–[105]. Looking at the loss profile of all DISCOs in Fig. 14 for FYs 2018 and 2019, it shows promising results for 2019 compared to 2018 with a significant drop in the percentage of losses. Yet, the results are not as per NEPRA's target and vary from

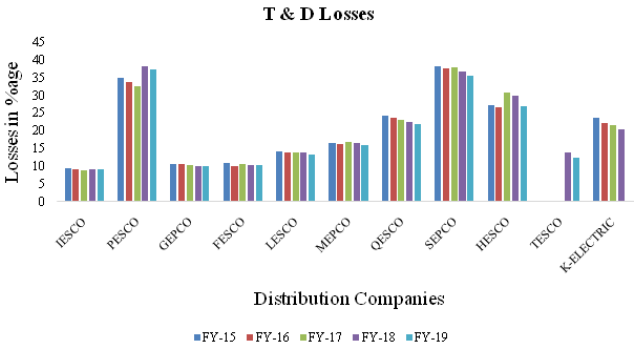


FIGURE 14. Trend of T & D losses occurring in different DISCOs of the country between 2015 and 2019.

DISCO to DISCO, owing to the nature of the terrain, line length, network deterioration, and theft. On the contrary, the K-Electric has been successful in reducing its line losses from 25.3% to 20.4% in four years and improving its recovery rate as well in most of the areas of the Karachi region. In the view of this loss profile, the utility network has gained much attention on its revival and maintenance under many strategic projects discussed in [106]–[111].

B. OVERLOADING ISSUES IN DISTRIBUTION NETWORK

The distribution of electricity through the utility network primarily depends on its three key components i.e. power transformer (132/11 kV), 11 kV feeders, and the distribution transformers (132/0.42 kV). Taking a close at their overloading statistics in Table 2 [43], overloading of power transformers as whole, is reduced from 30.28% to 23.01% in FY 2017−18. Individually, each DISCO has its own facts and figures such as; PESCO having a significant number of overloaded power transformers (approximately more than 50%) above 80% of their rated capacity, followed by MEPCO, QESCO, GEPCO, HESCO, SEPCO, K-Electric, FESCO, LESCO, TESCO, and IESCO. Among all, IESCO is the winner, which improved its loading conditions and showed only 0.81% of its power transformers being overloaded. Similarly, the overloading of 11 kV feeders all together diminished from 29% to 23.49% in FY 2017 − 18 as compared to the previous year. Independently, PESCO, TESCO, SEPCO, and QESCO have a higher percentage of overloaded feeders as compared to MEPCO, LESCO, FESCO, and HESCO, IESCO. Again, IESCO showed promising results with the least of its feeders were overloaded during subsequent years. Likewise, the overloading of distribution transformers reduced from 12.49% to 4.55% in FY 2017 − 18, compared to last year. Except for IESCO and GEPCO, the other DISCOs showed an improvement in their overloading conditions of distribution transformers.

Considering data in Table 2, the overall results show a high percentage of overloading on feeders and transformers, resulting in increased transmission and distribution losses and are unsatisfactory and reveal poor system performance [60]. Such system performance does not only cause loss of energy but also affects other sectors i.e. oil and gas and eventually the economy of country as a whole. To alleviate these issues, the modern technologies should be exploited for monitoring and control such as; using Automatic Meter Reading (AMR) [112], [113], Load Data Improvement Program (LDIP) [114], effective loss computation techniques, overloading detectors [115], net-metering for PV system integration [116] and many others.

TABLE 2. Data on total number of overloaded power transformers, 11kV feeders and distribution transformers (above 80%) in the different distribution companies of the country.

DISCOs	Power Transformers		11 kV Feeders		Distribution Transformers	
	2016-17	2017-18	2016-17	2017-18	2016-17	2017-18
IESCO	24	2	27	25	2,868	3,770
PESCO	113	125	485	412	21,033	618
GEPCO	34	51	88	59	1,475	1,741
FESCO	100	42	159	149	1843	392
LESCO	14	14	548	417	30,350	2,950
MEPCO	75	65	433	373	8,128	5,844
QESCO	75	55	233	211	8,873	7,094
SEPCO	53	49	167	157	7,424	3,736
HESCO	59	49	121	121	3,340	532
TESCO	14	14	199	207	—	—
K-E	57	48	91	29	551	478

C. RECOVERY OF DISCO's

Recovery of DISCOs has remained a major concern for the economy of the country, causing energy crisis, load shedding, and high tariff rates. Fig. 15 provides a comparison of recovery percentages of all the distribution companies including K-Electric for two consecutive years. For PESCO, its recovery dropped slightly by 0.69% in the succeeding year where TESCO showed a negative situation with its recovery rate dipped down by 16.29%. Similarly, the recoveries of IESCO, LESCO, MEPCO, HESCO, SEPCO, and QESCO were also affected negatively, with more drastic reductions

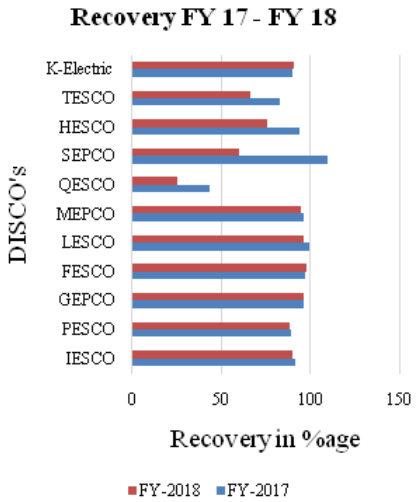


FIGURE 15. Recovery rate in different distribution companies of the country.

in the later three DISCOs. In contrast to them, GEPCO and FESCO showed slight improvement. However, due to the disappointing performance of most of the DISCOs, the overall recovery rate has seen a dip of more than 4%. On contrary, K-electric improved its recovery in FY-18 as compared to FY-17. Taking into consideration all, its again reiterated that higher T & D losses and low recovery rates in the country are effectively eroding the revenue beyond the acceptable levels and no real efforts or improvements are taken despite the regulatory directions to DISCOs and advisories to the executive body [43], [111].

D. CIRCULAR DEBT

Circular debt is a serious issue for the power sector and is highly influenced by T & D losses in DISCOs. Failure of DISCOs to comply with pre-defined regulations triggered an annual loss of around *USD*0.28 billion during FY $2017-18$ on the basis of the tariff. In continuation to it, the weighted average of T & D losses reported for FY $2017-18$ was 15.92% in contrast to 18.32% notified by DISCOs. Such disappearances generate doubts over the existing and upcoming monitoring strategies and techniques. Moreover, another factor contributing to circular debt is the low recovery rate of DISCOs. From the statistics of PEPCO, the overall recovery rate for DISCOs during FY $2017-18$ was around 87.71%. To ensure 100% recovery, it is desirable to set a consumer-oriented tariff, which helps in avoiding economic loss of *USD*0.95 billion annually [43].

In an ideal condition, the sum of bill revenue and technical losses should be equal to the cost of power generated plus supplied. But in the case of a country like; Pakistan, the inflows do not match the outflows, i.e. collections are always less than the cost of electricity generated. As a result, the fuel distributors are not paid for the fuel provided and in response, they stop fuel supply to generating stations. This results in under-utilization of installed capacity and ultimately causes energy shortage in the country and eventually worsening the circular debt further [15], [117].

VI. DISCUSSION

Based on the facts and figures obtained from the extensive investigations of the energy sector of Pakistan, it is possible to highlight the key system deficiencies leading to the energy crisis, as listed below [118]:

- Ineffective and incomplete energy mix with least share of renewable sources
- Higher dependency on fossil fuels for electricity generation
- Lack of proper management and planning strategies to control huge supply-demand energy gap
- Overloading of different power system components and rising share T & D losses in the utility network
- Unsatisfactory tariff rates and poor recovery of DISCOs
- Negligence of concerned authorities in upgrading the existing energy infrastructure
- Environmental issues due to excessive share of thermal power generation
- Under-utilization of installed capacity and inefficient power plants
- Alarming situation of growing circular debt

In spite of the fact that Pakistan is trying to mitigate its energy crisis, having direct or indirect effects on its economy, by balancing its energy mix with considerable renewable sources. But the historical dependence of the country on fossil fuels has strong roots to pull-out, which yet contribute to different environmental hazards like CO_2 emissions, greenhouse effect, global warming, and uneven weather patterns [119]–[121]. Presently, Pakistan is among those countries of the world which has significant contribution to greenhouse gases, accounting approximately 196.2 *million* metric tons of carbon dioxide emissions in the FY 2018 [122]–[127]. Even these days, Pakistan is encouraging coal-fired power plants to meet its rising load demand, and thus it's challenging for Pakistan to get control over its ecological profile. If it continues, it is predicted that by 2050, the contribution of Pakistan for greenhouse gases will hit 4621 metric tons, as compared to 347 in the FY 2011. Further, the import and rising price of crude oil have an economic and financial loss to country [128]. During $FY-2019$, 6.6 *million* tones of oil, costing *USD*3.4 billion was imported into the country as compared to *USD*2.9 billion during last year, which is an indication of a serious burden on the national treasury and further creates thoughtful doubts on the energy security of the country. Therefore, as reported in [129], [130], there is an urgent need to follow the global trend in replacing conventional sources with the country's extensive renewable sources, in order to ensure sustainable economic security and growth.

The modern renewable energy industry is now viewed as a cost-effective, sustainable competitor to fossil fuels and is expected to be the leading source of primary energy consumption by 2050 [131]–[133]. However, the energy demand in country is constantly growing annually by more than 9% and predicted to reach $8-fold$ and $20-fold$ by 2030 and by 2050 respectively [84], [134]. As shown in Fig. 16, Pakistan lacks behind leading countries i.e. China, Brazil, and the USA in utilizing its sustainable energy resources for electricity generation. Therefore, investing in renewable energy capacities can contribute to strengthening energy independence, lowering expenditures on fossil fuel imports, less susceptibility to international market price fluctuations and many others [135], [136]. Besides this, the gains from power generation are ephemeral, without addressing issues of the inadequate transmission network, an aging distribution infrastructure, power thefts, non-payment of unpaid bills, and energy conservation, [137], [138].

The existing transmission and distribution networks, operated by NTDC and K-electric, however, have shown positive results but are still constrained by overloading and line-losses issues which may cause undesirable tariff rates [60], [99]. Such condition is caused by multiple reasons

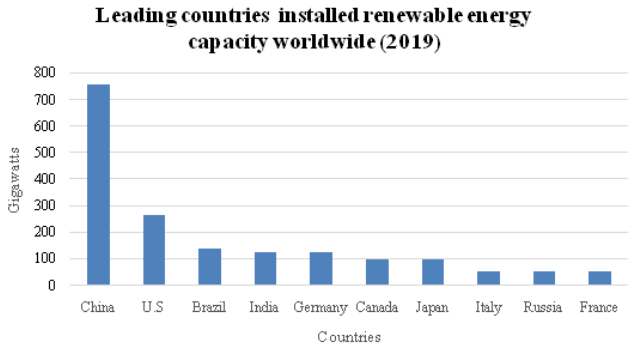


FIGURE 16. Installed power generation capacity of renewable plants in different leading countries globally [135].

including performance issues of DISCOs, lack of proper load-forecasting, insufficient size of the conductor, long distribution lines, inadequate placement of distribution transformers, low power factor, lack of reactive power control, improper load management, etc and need to be solved with proper installation and application of appropriate tools and techniques [139]–[145]. In addition to this, the management needs to be strict and transparent for proper investigation of all technical and non-technical issues and there should be no political interference in the operational and administrative matters of utility networks [146].

VII. PROPOSED REMEDIES AND STRATEGIES

This in-depth survey and analysis of the power sector in Pakistan reveals that the country must revise its policies, particularly for energy mix and supply networks. Further, the extra energy demand instead can be fulfilled locally with distributed generations mainly using solar and wind energies to lessen some burden on the main grid system. Based on the facts and figures discussed and analyzed, the following solutions are proposed to enhance the performance of the energy sector in Pakistan.

- It is clearly highlighted that most of the power generation is from fossil fuels with the least reliance on the available renewable sources which negatively affect the wealth and ecology of the country. Curtailing such over-dependence on the thermal generation and using alternative energy resources diminishes the circular oil debt on the nation and thus uplifts its economy and climate eventually.
- The country must utilize its enormous potential in solar and wind sectors with a cumulative of 130 *GW* to minimize the supply demand energy gap. Moreover, the northern areas of Pakistan are hilly in nature, small hydro-turbines can be installed over the waterfalls to generate electricity regionally where power transmission is itself challenging.
- The country has approximately 50 *million* animals for agricultural and livestock-related activities and on average, the daily bio-waste product is about 10 *Kg*. Using 50% of it accounts for 150 *million* kg of bio-waste that translates into around 12 *million* cubic meters of biogas. Biomass energy has appeared as an auspicious renewable energy source and has an enormous potential to meet the country's energy needs.
- The DISCOS have already introduced a net-metering system in the country to promote not only bi-directional energy flow but to control the line tempering which is a serious issue in the country. The Government still needs to take strict actions against the culprits to ensure the writ of the system in the energy sector.
- The country needs to upgrade its traditional power structure into a smart system, employing intelligent agents for monitoring and control. However, the contingency issues are every-where in the world and cannot be eliminated completely but can be detected and regulated if modern technologies and standards are installed and practiced, respectively.
- There are several techniques to reduce the T & D losses. The effect of T & D losses is very much broader and cannot be imagined easily. It is way started with equipment deterioration to economic losses. To overcome the technical losses, the DISCO's should place an optimal capacitor bank at the 11 *kV* feeder, where the load density is much high, it provides the reactive power locally and improves the voltage profile. In this regard, the concept of micro-grid can also be incorporated, which helps the DISCOs to overcome the overloading and reduces the T & D losses subsequently. Nevertheless, micro-grids also improve the reliability of electricity to control the problem of load shedding. On the other hand, the commercial losses can be reduced by the proper smart metering of distribution networks to the utility premises.

VIII. CONCLUSION

Keeping in view the serious issues of the energy crisis, supply-demand gap, economic and environmental damage, this detailed technical survey made on the energy sector of Pakistan has proposed and discussed the promising possible remedies and strategies to deal with them. The very first mistake, the country is making, is its over-reliance on thermal power generation which does not only raise the tariff rates in conjunction to fuel price variations but also brings economic and ecologic burden. Secondly, the transmission and distribution networks are outdated and poorly structured thus leads to increased power losses, and overloading and aging of system equipment which eventually degrades the performance of the entire power system of the country. To address these mistakes, the installation of renewable energy resources and retrofitting of new supply networks should be made.

Luckily, Pakistan is blessed with a vast variety of sustainable resources i.e., 1100 Km coastal belt for wind generation with the tendency of 50 GW, solar energy with an annual irradiance rate of $1900 - 2200\ kWh/m^2$ which accounts for 85 GW and small hydropower stations having the potential of 3100 MW. Further, transmission and distribution entities must take a lead not only to install new networks but also

to make the most of smart sensing technologies to ensure the abrupt supply and quality of power to the end-users. Although the country has few regulatory and monitoring authorities to oversee these problems and come up with a proper load management plan but due to the lack of modern technologies and techniques, such problems still persist in the system. Further, the level of performance of the system can be further improved by encouraging the user to become prosumers using distributed generations to not only minimize the losses but also to bridge the energy gap. Additionally, use modern tool and techniques i.e, autonomous robots and intelligent agents to do timely maintenance and mitigation activities for improving the operation and control of entire power system of country.

ABBREVIATIONS AND ACRONYMS

MOE - Ministry of energy, AEDB - Alternative energy development board, PPIB - Private power and infrastructure board, PEPCO - Pakistan electric power company, NTDC - National transmission and dispatch company, CPPA - Central power purchasing agency, GENCOS - Generation companies, WAPDA - Water and power development authority, KE - Karachi electric, NEPRA - National electric power regulatory authority, PAEC - Pakistan atomic energy commission, DISCOS = Distribution companies, O & M - Operation and maintenance, SEPCO - Sukkur electric power company, HESCO - Hyderabad electric supply company, LESCO - Lahore electric supply company, MEPCO - Multan electric power company, FESCO - Faisalabad electric supply company, QESCO - Quetta electric supply company, PESCO - Peshawar electric supply company, GEPCO - Gujranwala electric power company, TESCO - Tribal area electric supply company, IESCO - Islamabad electric supply company, NPCC - National power control center, RCC - Regional control center, CPP - Captive power purchaser, SPP - Small power purchaser, IPPs - Independent power producers, PV - Photovoltaics, T & D - Transmission and Distribution, HVAC - High voltage alternating current, HVDC - High voltage direct current, NREL - National Renewable Energy Laboratory, DNI - Direct Normal Irradiance, RLNG - Re-gasified liquified natural gas, RFO - Residual furnace oil, HSD - High speed diesel, AMR - Automatic meter reading, FY - Fiscal year, LDIP - Load Data Improvement Program, AJZ - Azad Jammu Kashmir, KPK - Khyber Pakhtunkhwa, GB - Gilgit Baltistan.

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