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Energy production system optimization: Evidence from Pakistan

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ABSTRACT

The ongoing energy crisis in Pakistan and the dependency on thermal electricity generation has contributed to the necessity to optimize energy production system. The expensive thermal electricity and inability to recover its cost gives unprecedented rise to the electricity tariffs. In this study, optimization of the energy production system has been performed using linear programing model. As the high cost of electricity generation has been found as the root cause of energy crises, the objective function of the proposed model is cost minimization that will also reduce the circular debt. Specifically, it has examined the optimum proportion of energy production from each available source under two different scenarios. The first scenario considers that the existing system should be used at its maximum capacity; in the second scenario, seventy percent utilization of power plants has been examined. The second scenario summarizes the optimum mix of energy production which minimizes the cost of electricity production. The differential cost that is payable by the government as a subsidy is also compensated. Similarly, it reduces circular debt that is a bottleneck between power generation companies and oil supply companies. Thus, the proposed model has a tendency to minimize the cost of energy production, and further reduce circular debt as well as the burden of a subsidy on the government. The study specifies the problems confronting Pakistan's energy sector and identifies the key elements of a potential policy response to address the country's severe power crisis.

1. Introduction

For sustainable growth and economic prosperity of any country in the world, the availability of electricity plays a critical role. In the case of Pakistan, a developing country with a growing population of over 200 million people, the need of electricity is ever on the rise. Moreover, the country's economy is mostly comprised of manufacturing sector [1]. Similarly, the manufacturing sector is heavily dependent on the supply of electricity [2,3] and Pakistan is suffering from severe energy crises [4–8]. Therefore, energy sector development needs special attention due to its vital role in the economy. Past studies have highlighted electricity as the life line of an economy [9–11]. Sahir and Qureshi [12] argued that in the era of intense industrialization, the production and supply of electricity is strategically essential for socioeconomic development. In addition, steady focus on the nation's economic development has created pollution; availability of electricity can also play a vital role in reducing pollution and cleaning the environment [13]. However, a fast increase in demand of energy and dependency on energy will be leading to the biggest problems of the world in the upcoming century [5]. The reason is that resources of energy production are diminishing day by day and the demand for energy is increasing [14,15]. Presently, the world is seen as global village, where energy is a strategic source that would result in wars [16,17], and further, it can also smooth the economic development of any nation [1,3]. Moreover, due to materialistic lifestyles of the people, energy does not only play a vital role in the production process, but also has equal importance in consumption patterns of any country [18]. Therefore, production and the supply of energy is not only important but also considered as a backbone of the world economy [19]. Existing literature has highlighted the importance of energy and suggests that energy is considered as a most important determinant with respect to other variables of economic progress [10,20,21]. That's the reason energy variable is included in production and consumption pattern of countries which are the intermediate level of economic progress [22].

At its current, Pakistan is facing severe energy crises and most of Northern areas are still not linked to national grid. According to Rafique & Rehman [5] the gap between energy supply and demand is large and increasing day by day due to limited resources for producing electricity. However, Pakistanis were enduring as much as 10–12 hour load-shedding in urban areas whereas in rural areas, electricity remains unavailable for 16–18 hours in a day [5,23]. This severe energy crisis has affected every sector of the economy even a common man. The unavailability of electricity is due to the shortfall of energy production. Previously, the initiative to build massive dams like Mangla and

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Tarbela in the 1970s prevented Pakistan from major energy crises at that time [24]. However, those decisions worked for a short span of time as hydro driven electricity successfully fulfilled the demand of that time. But, Pakistan has achieved high economic growth through industrialization during the era of 1980s [25], however no initiative has been taken to upgrade the energy supply structure [26,27]. Moreover, with the passage of time population of the country increased [28], urbanization has generated the installment of new industries and other customers of energy in the corporate sector. This high demand of energy has contributed to the worse situation in the energy sector of Pakistan. According to Kugelman, the shortfall of electricity reached 8500 (MW) during June 2012, which is almost 50% of national demand [24].

Pakistan is a developing country, its economic structure, transportation technologies, consumption patterns and life style of people are totally different from developed countries. Pakistan is blessed with natural resources to produce cheaper energy in the country, these resources consist of hydro, solar, coal and wind power [5,6,8,29,30]. Currently, Pakistan's main sources to produce electricity are oil and gas, the cost of electricity production from these sources is much higher as compare to other available sources [7,27]. According to the National oil and gas Development Company of Pakistan, if focus remained on only these resources (oil and gas) to produce electricity, it will result in exhausting of these resources by 2025 and country will run out of these resources. Currently, Pakistan is producing maximum thermal energy from oil [31,32]. However, the cost of electricity generation from oil is higher than the tariff charged by the government of Pakistan [33]. Similarly, the difference between the cost of electricity generation and the final price charged to consumers is payable by the government as a subsidy. However, the government can't afford the huge amount of subsidy due to limited resources. Thus, the failure of the government to pay the differential cost to power generation companies results in the form of the circular debt [34,35].

The circular debt in the energy sector of Pakistan emerged in 2006, when oil prices in the international market were increased to high level. The government decided to freeze the power tariff, as passing the high oil prices to the power tariff would have been a politically sensitive decision. However, first time circular debt reached at PKR 111 billion in 2006, whereas it reached at PKR 480 billion in 2013 [33]. The government has paid outstanding circular debt to address the energy crises in Pakistan. This decision significantly influenced the energy sector and shortfall is reduced to 4760 (MW) which is not much higher as compared to the shortfall in 2012 but still there is 10–12 hours load-shedding in urban areas of the country [36].

Previous studies [26,34,35,37–40] have consensus that the circular debt is one of the major causes of electricity crises in Pakistan. However, scientific literature is silent at providing a mechanism to address the issue of circular debt in the context of energy sector of Pakistan. Therefore, we believe, it is a knowledge gap in academic literature. In addition, the cost of electricity production is highly dependent on fuel prices, adequate production and transmission structure [27,41]. Further, energy theft, poor management, underutilization of power plants, line losses, circular debt and high dependency on thermal electricity are also the causes of high prices of electricity [26,41]. However, the current shortfall is due to the reduction in the generation of electricity by the Independent Power Producers (IPPs) due to shortage of oil and gas supply [36]. This shortage in energy supply is due to non-payment of funds to the oil supply companies by the government because the amount which government needs to pay against the subsidy hasn't been paid yet. However, current energy crises can be managed by optimization of infrastructures, utilization of existing resources, strong financing, realistic planning and partnership with private sector and international agencies [32]. But, the high cost of electricity generation and high circular debt are the hurdles in addressing energy crises and optimization of energy production. Hence, we believe there is a direct relationship between the circular debt and cost of electricity production. Consequently, the government needs to address the issue of circular debt for optimization of power plants.

Therefore, the objective of this study is to design a model for energy production system optimization that can be used to control the load-shedding and reduce the burden of subsidy. So, this study proposed an optimal energy production mix that minimizes the cost of electricity generation. As cost minimization can reduce per unit tariff, the difference between the cost of production and tariff charged to the final consumer becomes lower that minimizes circular debt as well as the burden of a subsidy on the government. Moreover, reduction in circular debt escalates the payments that not only increase oil supply to thermal power plants but it also makes funds available for other power plants to improve their efficiency. Finally, it raises the production level of power plants to minimize load-shedding in the country.

The study is organized as follows. Section 2 presents the background of the energy sector in Pakistan. It discusses the overall energy production mix in the country, the average load-shedding in different regions and further it also elaborates on key players involved in the energy sector of Pakistan. Section 3 briefly elaborates on the model formulation and it's testing to validate the results from a proposed model. Finally, this study concludes with policy implications in Section 4.

2. Background of energy sector in Pakistan

Pakistan is a developing country in South Asia, suffering from severe energy crises. The high cost of energy generation, burden of subsidy, shortage of funds, high circular debt, poor planning, intense reliance on imported fossil fuels and mismanagement of power infrastructure are the main causes of these energy crises [5,32,33,42]. The less utilization of cheap alternate energy sources like wind, hydro, solar and coal makes problems more intense for power sector of Pakistan. According to the NEPRA report of 2014, Pakistan has total installed capacity of 24,953 (MW) and current demand of the country is 18,000 (MW). These figures indicate that Pakistan has an enough installed capacity of energy production, and it can easily fulfill the existing demand of the country [31]. Thus, there should be no load-shedding in the country. But, the current energy production system (energy production mix) is unable to fulfill the existing demand of the country and urban areas of Pakistan are facing 10–12 hour loadsheding while rural areas are facing 16–18 hours [5].

The recent data from government sources (APP) indicates that the current system is producing 13,240 (MW), 4760 (MW) lesser than the total demand of the country [36]. Fig. 1 below indicates the installed capacity of electricity and highlights the overall energy mix, which mainly consists of thermal sources. Almost 68% of installed capacity is skewed toward thermal sources and Pakistan produce 87% of current electricity using thermal resources [32]. The cost of electricity generation from thermal is higher as compared to other available sources. In addition, the tariff charged to the final consumer is low as compared to the cost of electricity generation. The difference between the cost of electricity generation and the final tariff charged to consumers is

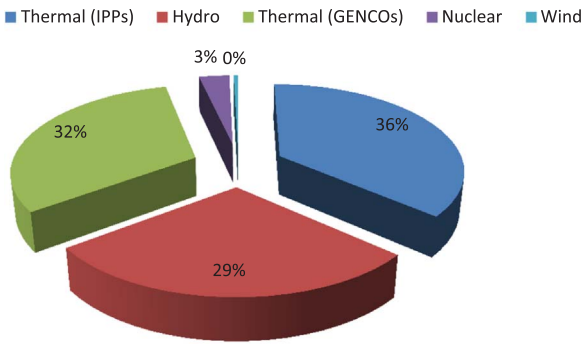

Fig. 1. Pakistan's installed capacity of energy production.

payable by the government as a subsidy [33]. However, the government has started to reduce subsidy for power sector [43] because the government can't afford the huge amount of subsidy due to limited resources.

Meanwhile, hydroelectricity production is a better option for cheap electricity generation and it can minimize the subsidy but the contribution of hydroelectricity is small in Pakistan's overall energy production mix. The overall energy production mix is skewed toward thermal which results in the high cost of the electricity generation due to increase in the prices of fossil fuels [44]. The high cost of electricity generation results in high circular debt and a higher burden of the subsidy that worsens the reliability of thermal power plants due to availability problems of fossil fuels. Additionally, the governance structure, corruption, mismanagement and shortage of funds are the biggest challenges of power sector in Pakistan [27,41,42,45]. Energy policy of the country is also complicated because this policy is under the umbrella of many ministries and agencies of the government which lack coordination among each other. There is war of authority between these agencies due to lack of clear line of authority. The energy sector of the country is also suffering from electricity theft and inefficiencies of the system which includes more than 25% transmission and distribution losses [46]. To minimize the transmission and distribution losses the government has taken an initiative and reduced power supply to those areas where these losses are higher. As a result, the load-shedding in these areas increased but the overall transmission and distribution losses reduced from 25% [46] to 16.9% [34]. However, the most important factor is the shortage of money that is considered as one of the biggest deficiency plaguing the energy sector [24,47]. Few years ago, in July 2012, Pakistan's economy was struggling to overcome the liquidity problems but in 2014 Pakistan has improved its level of liquidity condition [48]. Still the consequences of liquidity problem are there and consumers of the energy sector, distribution companies, the national transmission agency and the government itself are unable to pay their electricity bills on time [49].

The data provided by the Water and Power Ministry of the country indicates the "influential defaulters" owe around $ 1 billion in outstanding power bills [24]. These influential defaulters mostly comprise of the government and its different departments. However, the energy sector of Pakistan needs revenue on the urgent basis to address the current energy deficiency by paying expenditures of electricity generation, its transportation and distribution, as well as the administrative and operating cost of the energy sector. The difference between expenditures and revenues is considered as circular debt. Recent data indicates that circular debt reached to almost PKR 600 billion that is the worst condition for the energy sector [50]. Over the past decade, the government of Pakistan has paid millions of funds in order to minimize the circular debt, but it remains increasing with the passage of time [34]. The core reason is that the tariff charged to end consumer is always low as compared to the cost of electricity production. As the government funded subsidies are the major source to balance the difference between the cost of production and tariff charged to the final consumer, whenever the government fails to balance this gap, it becomes the circular debt [33]. Moreover, Pakistan being a developing country has limited resources as compared to developed countries and unable to pay the circular debt. This situation causes the reduction of oil supply which in a result interrupts the production and supply of electricity. Accordingly, hurdles in oil supply influences the electricity generation. So we believe, if this interruption handled successfully then Pakistan can minimize the load-shedding in the country. Fig. 2 given below shows the load-shedding comparison of different regions from 2010 to 2014 and it can be seen that the situation today is almost similar to the situation of 2010.

On the other hand Mughal argues that due to wrong decisions of bureaucracy, petrol crises of 2015 brought difficulties for common people and reduced electricity production. Additionally, he said, despite record receivable of PKR 235 billion, the circular debt of the

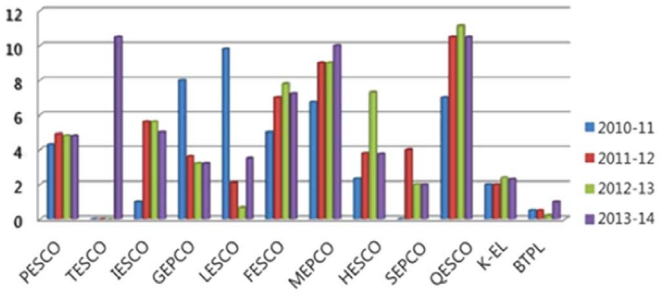

Fig. 2. Average duration of load-shedding (Hours).

energy sector crossed PKR 600 billion as officials ignored the dilemma of Pakistan State Oil (PSO). While PSO started to default its obligations in November, 2014 and financial institutions rejected their loan request. Moreover, in the same month PSO faced a fine of PKR 250 million by financial institutions, PKR 180 million demurrage charges and damages claim to the tune of PKR 65 million by foreign oil suppliers but it was not enough to get attention of the policy makers. Unfortunately, the indifferent attitude of authorities helped the circular debt engulf the whole country, punish masses and hurt limping industry that should be addressed to overcome energy crises in Pakistan [50].

Consequently, there is a direct relationship between electricity crises and the circular debt in the energy sector of Pakistan [44]. Because, when operating unit is facing difficulty with outstanding receivable, in return, this unit holds back payments to its contractors and creditors. It creates a bottleneck among oil suppliers and energy production units. In the context of energy sector, it can be noted that the circular debt arises due to the prevailing amount of subsidy and bills payable by different departments of government. The overall profile of the energy sector in Pakistan is drafted by Ali and Badar [40] as indicated in the study of Kessides [26] and Rafique & Rehman [5] shown in Fig. 3. The model highlights two subsidies that the government pays against oil and electricity [26]. However, it can be seen in the flow diagram that cash flow problem in one operating entity significantly affects other entities in a payment chain [35,40]. For example, Pakistan Electric Power Company (PEPCO) is responsible for the power supply to all government departments, private sector including KESC and it is also responsible for tariff collection. The revenue collected by PEPCO is distributed to oil marketing companies and independent power producers (IPP's). If PEPCO faces delay in payments from government or any other entity, it will lead to delay in payments to oil marketing companies and Independent Power Producers (IPP's). Similarly, PEPCO's cash flow problem significantly affects the other sections of power supply chain [51]. This is the emerging point of the circular debt problem. Moreover, the main cause of circular debt is the failure of distribution companies because these companies failed to collect dues from individual consumers including provincial governments. As a result, distribution companies failed to settle their payments with power generation companies and Independent Power Producers (IPP's). Similarly, power generation companies and Independent Power Producers (IPP's) are facing difficulty to pay against fuel purchased from oil marketing companies. As a result, oil marketing companies' delay settling their dues to refineries. Moreover, ineffective contractual schedules of PEPCO and KESC are also major contributors to inter corporate debt problem [26].

Circular debt was reported PKR 420 billion and PKR 584 billion by independent experts during July and September 2010 respectively [52]. However, to address this problem, the government probed the issue and found that circular debt is PKR 665 billion that is much higher than the reported amount [52]. At the end of 2011, the government has paid PKR 360 billion against the circular debt to address energy crises. Likewise, during May 2012 PEPCO's receivables again reached to PKR 360 billion. As a result, PEPCO has significant arrears to oil marketing

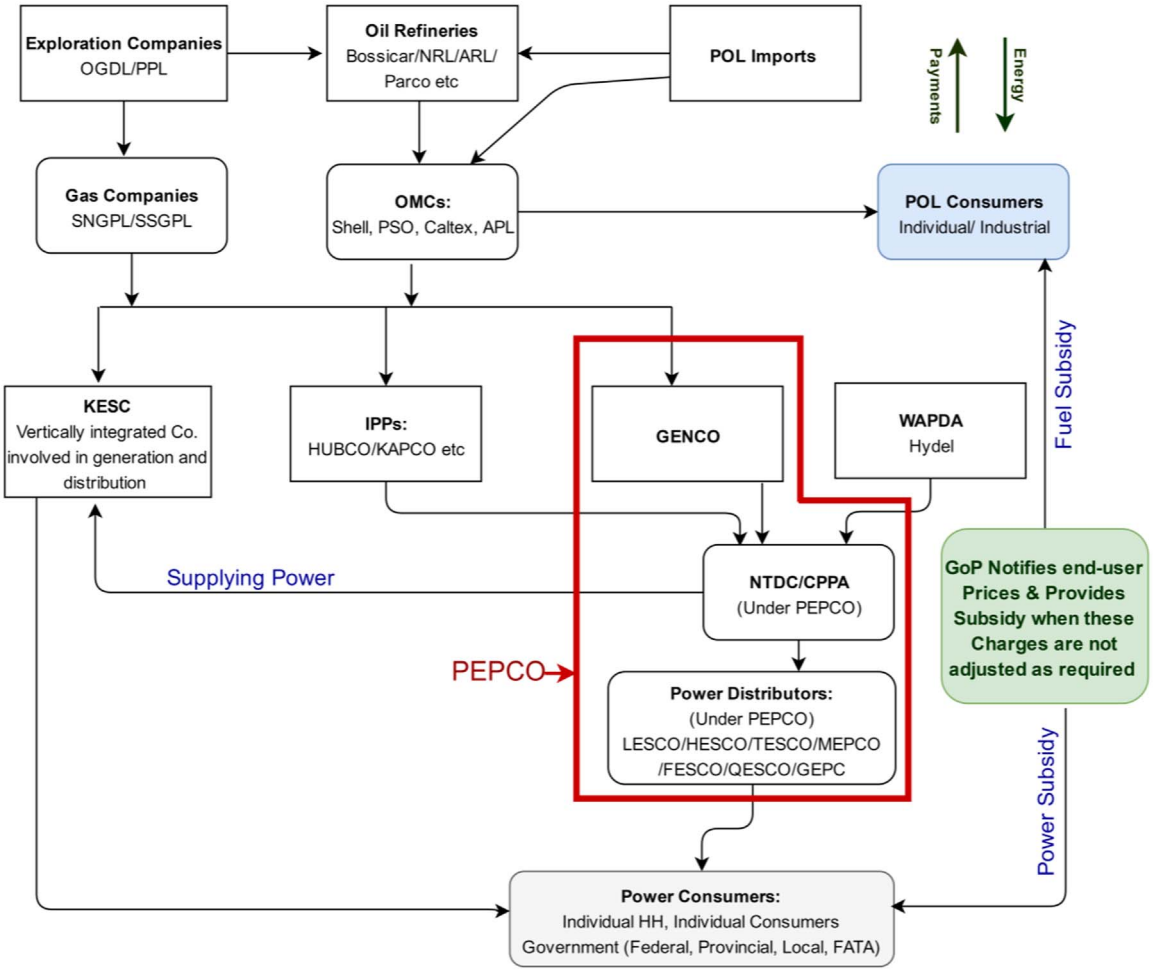

Fig. 3. Major players involved in energy sector.

companies and Independent Power Producers (IPP's). Due to the continuous increase in circular debt, well performing state owned entities such as Sui Northern Gas Pipelines Limited, Pakistan State Oil, and Sui Southern Gas Company are on the verge of financial collapse [26]. This situation has badly affected oil refineries which lead them to operate at lower capacities due to crossing their borrowing limits from banks; consequently, the oil refineries failed to import crude oil for a long period. Default of oil refineries results in shutdown of power generation plants that further exacerbate the country's already severe power shortages [53].

Delay in payment of the promised amount of subsidy to the PEPCO and its affiliated DISCOs, bound their capacity to pay their own liabilities for the purchase of electricity [35,51]. Additionally, bank wide analysis shows that loans extended by public and private banks to the power sector in Pakistan was concentrated in the top five banks. These banks have almost reached their exposure limits for power industry. Therefore, banks are reluctant to fund any new power project. This is particularly serious because the account for a very large share of five major banks traditionally extended credit to the power sector. Moreover, the circular debt is also a hurdle for new power projects [54]. The government needs to clear circular debt first, so that banks can extend credit for new power projects. To handle electricity crises it is highly important for the government to pay attention to the circular debt. However, the issue of circular debt emerges due to non-payment/delays of subsidies and the high cost of production that would result in underutilization of power plants installed capacity, which ultimately causes energy deficiencies in the country. The government has planned to reduce PKR 200 billion in circular debt by June 2018 and to keep subsidies to 0.4% of GDP (Gross Domestic Product) [37].

The cost of electricity generation in Pakistan is very high as compared to neighboring countries due to the current electricity generation mix. The study of Wakeel, Chen, & Jahangir [32] has indicated that Pakistan's main source of electricity production is thermal, as 87% of electricity produced in the country is based upon these sources. The electricity produced using thermal results in high cost [37,44]. To compensate the end consumers, the government gives subsidy. Due to inadequate resources and poor planning, most of the time it fails to pay the amount of subsidy which results in high circular debt [39,55]. However, the circular debt is a bottleneck between oil supply companies and power plants [44]. According to the study of Kessides [26] Pakistan's current electricity generation mix has created worst condition with severe consequences for the energy sector as well as economic security. Due to severe energy crises, during the last five years more than 40% of textile industry shifted to Bangladesh [38]. Malik [56] suggested that Pakistan should change its energy production mix to streamline the country's electricity generation. Moreover, in order to ease its vulnerability to oil price fluctuations, changing energy production mix is highly significant.

Globally, electricity is generated with Coal, Gas, Hydro, Nuclear, Oil and other renewable sources as 31%, 26%, 20%, 6%, 7% and 10% respectively [57] but in Pakistan the major source of electricity production is thermal [58]. The cost of electricity produced from these sources is much higher than the other available sources [32]. Though, the cost of electricity production depends upon many factors but the main factor is the source of production i.e. Coal, Gas, Hydro, Nuclear and Oil. Additionally, energy theft, line losses, underutilization of power plants

and poor management also increase the overall cost of electricity [55,59]. However, the government has a plan to reduce the share of oil in producing electricity and it aims to minimize it to 19% in 2020 [60]. According to the Gazette of Pakistan, the overall cost of electricity generation is determined by the National Electric Power Regulatory Authority (NEPRA) at the relevant stage. However, the government provides subsidy to facilitate end consumers. Currently, government is paying subsidy of PKR 3 per unit for consumers using below 200 units, and PKR 0.80 per unit for the consumers using above 200 units per month. Previously, to reduce the cost of producing electricity, most of the studies focused on the importance of renewable sources [29,37,55,61–63]. But, the installation of new energy projects needs injecting of a large sum of money and it takes a long time. However, to address current energy crises, the only way in short-run is to focus on efficiency of available sources by utilizing their maximum installed capacity [27].

The important elements of Pakistan's energy crises include the high cost of energy generation, burden of subsidy, shortage of money, high circular debt and mismanagement of power infrastructure. Additionally, poor planning and low level of implementation are also creating worse situation for the energy sector in Pakistan. This situation threatens Pakistan's economic development and the social welfare of individuals is also compromised. It can be argued that the government needs to address energy crises actively as the country is already paying high cost due to these crises. However, to address the energy crises, the energy production system optimization and optimal energy production mix creation for current and future energy policy development seems highly significant.

3. Methodology

The scientific literature has indicated that there is a relationship between energy crises and cost of electricity generation [44]. The cost of electricity generation is determined by NEPRA, as most of electricity generation in the country is based on thermal [32]. The high cost of electricity generation has put high burden of subsidy on the government. Consequently, the most critical factor is the cost of electricity production that can be considered as the root cause of energy crises in Pakistan. Therefore, to address the energy crises and safeguard Pakistan from oil shortage, this study designs a model, which compiles an electricity production mix to reduce the cost of production and also decreases dependency on oil to produce electricity.

Given the nature of the problems of energy sector, the model has focused on the optimization of energy production system. The study has emphasized on the cost minimization as the difference between the cost of production and tariff charged to the final consumer becomes lower that minimizes circular debt as well as the burden of subsidy on the government. Moreover, reduction in circular debt escalates the payments that does not only increase oil supply to thermal power plants but also makes funds available for other power plants to improve their efficiency. Finally, it raises the production level of power plants to minimize the load-shedding in the country. The study used the five different sources of energy production and designed an optimum mix of energy production where the cost of energy production is low.

The subsequent section describes data sources, model formulation, its working and the methods used to analyze the model.

3.1. Data sources

We apply the linear programing model to create optimum mix of energy production. The data has been collected from annual report of NEPRA 'State of the Industry Report 2014' [31], Power Statistics of Pakistan 2013–2014 of the National Transmission and Distribution Center [64], Pakistan Energy Year- book 2014 of the Hydrocarbon Development Institute of Pakistan [65] and Economic Survey of Pakistan of the Ministry of Finance [28]. These reports have provided the cost of electricity generation from each power plant. However, to achieve the objective function, we grouped production units into five categories (Thermal IPP's, Hydro, Thermal GENCO, Nuclear, and Wind). To achieve per unit (kWh) cost of electricity generation, this study accumulates the cost of production from each group and divides with the total electricity units produced from that group as suggested by Imran & Amir [27].

3.2. Model formulation

This study presented a linear programing model to design an optimal mix of energy production. There are different sources of electricity generation like thermal, hydro, nuclear and wind, but each source has some limitations. The proposed model can include different energy sources and it has the tendency to compile an optimum electricity production mix to reduce the cost of production and it also decreases dependency on oil to produce electricity.

$$C = min \sum_{i=1}^{n} kixi \tag{1}$$

where, C is the total cost of production from all sources. The objective function in (1) is the summation of products output-price per unit from each source. K is the unit cost of electricity production and x is the production of electricity from each source. However, the objective of our model is to minimize the cost of electricity generation by creating an optimal energy production mix based on the output from all sources.

The minimization of the cost (objective function) is subject to the six constraints. To increase the production level with minimizing cost we have restricted our model with constraint (2). This constraint engages the minimum acceptable cumulative output from all sources which should as a result increases the current production of electricity to reduce load-shedding, where, z is the minimum acceptable production level of electricity. Per unit (kWh) cost of electricity generation is fixed in the model.

$$\sum_{i=1}^{n} xi \geq z \tag{2}$$

Independent Power Producers (IPP's)

$$\sum_{i=1}^{n} IPP \leq T \tag{3}$$

GENCO (Government owned Production Units)

$$\sum_{i=1}^{n} GENCO \leq TG \tag{4}$$

HYDEL

$$\sum_{i=1}^{n} HYDEL \leq H \tag{5}$$

NUCLEAR

$$\sum_{i=1}^{n} NUCLEAR \leq N \tag{6}$$

WIND

$$\sum_{i=1}^{n} WIND \leq W \tag{7}$$

Independent power producers (IPP's) are privately owned electricity production companies that use thermal as a source of electricity generation. In this study, we restricted (3) the input in a model for IPP's. So electricity generated from IPP's can't be more than the total production capacity of independent power producers (IPP's), where, T is used for the entire production capacity of IPP's.

GENCO is the electricity production from the government owned power plants called generation companies (GENCO). It also uses thermal as a source of electricity generation. In the proposed model electricity production from GENCO (4) is restricted. So electricity generated by GENCO can't be greater than its total capacity, where, TG is used as the entire production capacity of electricity from GENCO.

HYDEL is the electricity production capacity of Hydro based power

plants. The input in the model for Hydro power plants can't be greater than the total production capacity of the system. Thus, we have added restriction in our model (5), where, H is the total production capacity of the country based upon hydro power plants.

NUCLEAR is the electricity production capacity based upon Nuclear power plants. We have also put restriction in our model (6) that production from Nuclear power plants can't be more than the total production capacity of Nuclear power plants, where, N is the total production capacity of Nuclear power plants. Moreover, Pakistan also has a little capacity of renewable energy. The WIND (7) is the electricity production capacity based on wind power plants. We also added a restriction in the model for this system. So that energy production from the wind based power plants can't be greater than the total production capacity of Wind based power plants, where, W is the total production capacity of wind power plants.

3.3. Empirical estimation and discussion

Once the model established and constraints have been designed, the next step is testing the validity and reliability of the proposed model. To empirically test the model in the context of energy sector of Pakistan, the study has designed two different scenarios that can confirm the reliability of our proposed model. The first scenario has assumed that Pakistan should effectively utilize the available energy production system by operating power plants at their installed capacity and generate more than 24,000 (MW) of electricity. To do so, we have applied the proposed model; results are shown in the Table 1 given below.

3.3.1. First scenario

The results from the Table 1 indicate that if Pakistan operates power plants as per their installed capacity then per unit (kWh) cost of electricity production will be PKR 11.28 (kWh). However, enough electricity would be produced (24,000(MW)) that can successfully eliminate the energy shortage in the country. The energy production mix is not feasible because power plants in the country don't have capability to operate at their full capacity. As the study of Ullah [66] indicates that some of the power plants are very old and they need to be overhauled but overhauling need effective management, policy reforms and as well as the cost. Corruption and poor management are the main hurdles in improving the operating capacity of power plants [35]. Operating at 100% installed capacity is not possible as Haider and Rasli [67] argued that reasons to operate at lower capacity include incompetency, bad governance and the main reason is that the government don't have political will to solve the issue. But, there is space to improve the operating capacity of installed power plants because during festivals and special occasions, same power plants operate at better capacity as compared to their current operating capacity.

Additionally, as noted above currently Pakistan is producing 13,240 (MW) of electricity that is not enough to fulfill the current demand of the country. However, most of the electricity is being produced using thermal [41]. According to the data provided by NEPRA [31] the cost of electricity production from thermal is more than 15 PKR per unit (kWh). This higher cost of electricity production is the main cause of lower production because it creates circular debt and the circular debt is a bottleneck between oil supply and electricity generation in the country [33,35].

Table 1
The Case of production more than 24,000 (MW).

LP(Linear Programing) Model Solution Objective Function Value achieved: 1) 270,649.5	
VARIABLE (Source of Production)	**VALUE (Electricity Produced)**
X1 (Thermal IPP's)	9083.0000
X2 (Hydro)	6927.0000
X3 (Thermal GENCO)	7097.0000
X4 (Nuclear)	787.0000
X5 (Wind)	106.0000
Optimal solution found at 4th Iteration	

Table 2
The case of minimum acceptable level more than 15,000(MW).

LP(Linear Programing) Model Solution Objective Function Value achieved: 1) 161,374.0	
VARIABLE (Source of Production)	**VALUE (Electricity Produced)**
X1 (Thermal IPP's)	6360.0000
X2 (Hydro)	3047.0000
X3 (Thermal GENCO)	4968.0000
X4 (Nuclear)	551.0000
X5 (Wind)	74.0000
Optimal solution found at 5th Iteration	

3.3.2. Second scenario

The second scenario from proposed model indicates the optimal mix of energy production that further confirms the validity and reliability of the model. The minimum acceptable production level has been entered as 15,000 MW (minimum acceptable production level); the output is shown in the Table 2 given below.

The results from second scenario have been summarized in the Table 2 that indicates the optimal and feasible mix of energy production in the country using the proposed model. The proposed optimal mix can be achieved if the government ensures the productivity of power plants at minimum acceptable level as proposed in our model. Thermal based power plants are already running at seventy percent of their installed capacity, the government needs to ensure the energy production of other power plants at seventy percent of their installed capacity to optimize the energy generation mix. However, our model proposed that the government needs to inject some money for overhauling of hydro, wind and nuclear based power plants instead of paying a large sum of money against circular debt after almost every quarter. This overhauling will result in better productivity of hydro, wind and nuclear based power plants that will create an optimal energy production mix for the country. Moreover, the proposed optimal energy production mix will reduce the overall cost of energy production. The minimized cost will shorten the difference between the cost of energy production and the tariff charged to the final consumer. Currently, the production level in the country is 13,240 (MW) and the production mix is highly skewed toward thermal. The cost of production is almost as high as PKR 15 per unit (kWh) that is resulting in high circular debt. The circular debt emerges due to the high cost of electricity production; further, it disturbs the optimization of power plants.

Additionally, we believe proposed model is useful enough for policy makers, in designing energy policy, to overcome current energy crises in Pakistan. Using the proposed model of energy production system optimization, the production level will increase to 15,000 (MW) and the cost of energy generation will be minimized to PKR 10.75 per unit (kWh). The increase in production level will automatically reduce the load-shedding up to 2–3 hours. Additionally, the lower cost will minimize the gap between the cost of production and tariff charges to the final consumer. Shortening of the gap can reduce the circular debt as well as the burden of a subsidy on the government. Finally, reduction in circular debt will escalate payments to production companies that raise the production level of power plants.

The government is paying almost PKR 3 per unit (kWh) as subsidy to compensate end consumers while the proposed model reduces the cost of production by PKR 4.25 per unit (kWh). The difference between the cost of production and the tariff charged to the final consumer will be diminished by using the proposed model. Moreover, the results for scenario 2 of the proposed model indicate that the government will get

more than PKR 1 in a surplus which can be further used in compensating transmission and distribution losses.

4. Conclusion and policy implications

4.1. Conclusion

This study has highlighted that the high cost of energy generation, circular debt and burden of subsidy are the root causes of energy crises in Pakistan. In addition, the study has indicated that there is direct relationship among cost of energy production and circular debt, whereas, the burden of subsidy is the main cause behind creation of circular debt. Therefore, to address the root causes of energy crises, the optimization of the energy production system has been performed using LP (linear programing) model. As the high cost of electricity generation has been found as the root cause of energy crises, the objective function of the proposed model is cost minimization. Two different scenarios have been developed and examined. The first scenario considers that the existing system should be used at its maximum capacity; in the second scenario, seventy percent utilization of power plants has been examined. The second scenario summarizes the optimum mix of energy production. The optimal mix of energy production minimizes the cost of electricity production to PKR 10.75 per unit (kWh). The differential cost PKR 3 per unit (kWh), that is payable by the government as a subsidy is also compensated. Similarly, it reduces circular debt that is a bottleneck between power generation companies and oil supply companies. Once the bottleneck has been bridged, the timely payments to energy generation units would be possible. So, oil based power plants can timely pay their bills and other power plants can improve their productivity with timely available funds. Finally, the availability of funds will improve efficiency of power plants that will raise the production level to minimize the load-shedding in the country.

4.2. Policy implications

To address the energy crises, the government of Pakistan needs to formulate a short-term and long-term energy policy. The short-term energy policy should emphasize the optimization of existing power plants while long-term energy policy requires the steps more structural in nature along with political and institutional commitment.

In the short-term, the government needs to emphasize the better allocation of resources. As this study has highlighted that circular debt is a bottleneck among power generation companies and oil supply companies. The government should immediately address the issue of circular debt and restructure revenue collection system to stream-line payments to energy production companies. Once the issue of circular debt is addressed, the government should dedicate financial resources for overhauling of power plants instead of paying a large amount against circular debt almost after every quarter. In this way, the funds become available for power generation companies which will emphasize their productivity. The increased productivity of power plants will supply more electricity for the economy. As the industries are shifting from Pakistan to Bangladesh, the optimization of power plants can be a short-term solution to encourage industries to continue their operations in Pakistan. In addition, it is also important to penalize the bad collection of revenues to control over power theft. The high cost of electricity generation and creation of circular debt are the main culprits behind the energy crises of Pakistan. Therefore, along with energy production system optimization the government should ensure a reasonable control over the minimization of circular debt. This should be immediately addressed otherwise it will be difficult to address power crises in the country.

In the long-term, the increased energy capacity should be added to power sector. In addition, the government should emphasize shifting energy production from thermal to other available sources which can produce cheap electricity. Moreover, the construction of Kalabagh and Diamer-Basha dam, Pak-Iran gas pipeline and completion of Neelum-Jehlum hydro project should be emphasized in the long-term planning. And also, for shifting energy production from expensive thermal to alternative sources, the short-run hydro projects should be emphasized in formulating energy policy of the country.

Pakistan has huge potential to produce cheap electricity from wind. The area has a coastal line of 1100 km (km), endowed with huge potential of wind energy. But the country is producing a small part of energy from the wind. Thus, in the long-term the government should consider wind energy as an alternate source. It will improve the power situation in the country, and also it will enable Pakistan to produce cheaper electricity. Unfortunately, the policy makers put emphasis on the installation of more thermal based power plants. The government has no control over supply of oil and gas as well as their prices. As the prices of oil and gas increase in the international market, the per unit power tariff also increases which puts more burden of subsidy on the government. As the burden of subsidy increases, the circular debt also increases. This strategy is highly risky and it creates alarming condition for energy sector because most of the oil consumed in Pakistan is imported from other countries and its price is not under the control of the policy makers of Pakistan.

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