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Electricity Economics and Integrated Resource Strategic Planning

ZHAOGUANG HU

Electricity supply economics and electricity demand economics are the two major components of electricity economics. This paper discusses the production functions with electricity, a core principle of electricity demand economics. In this paper, production functions with electricity are introduced at the firm level, sectoral level, industrial level, and national level. This paper also discusses integrated resource strategic planning (IRSP). As a part of electricity supply economics, it is a useful tool for policy study on low-carbon electricity. During the national economic development, low-carbon electricity can be recognised as the IRSP and the implementation of smart grid. The low-carbon electricity would be a great roadmap to Pakistan's economic development. Pakistan's economy is in an early phase of industrialisation. China's economy is in the late phase of industrialisation. Experiences and lessons from China's economic development would provide references to Pakistan.

Keywords: Electricity Economics, Production Functions with Electricity, Integrated Resource Strategic Planning (IRSP), Low-carbon Electricity, Pakistan, China

1. INTRODUCTION

What is electricity economics? This is a popular topic that receives global attention from all quarters. Electricity economics consists of two parts: electricity supply and electricity demand [Hu and Hu (2013)]. On the electricity supply side, it studies the economic issues in the electric power sector, including topics of: economic operation of power system, economic analysis of power plant construction and operation, power sector regulation and deregulation, power generation expansion planning, electricity tariff, economic analysis of power transmission and distribution. It is based on the fundamentals of economics to study and solve the electric engineering problems on power supply side. For example, generation expansion planning is to optimise the power resources such as hydro power, nuclear power, coal-fired power, gas/oil power, wind power, solar power and etc. to get the best profits or least cost from technical and economic perspectives [Yuan, Kang, and Hu (2008)]. It investigates optimal allocation of resources and electric power supply [Stoft (2002)]. How to improve productivity of power system is also discussed by many economists and researchers [Rothwell and Goméz (2003)], which is called electricity supply economics [Zhang and Shen (2005)], or electric power (system) economics.

Zhaoguang Hu <zghu@public3.bta.net.cn> is Vice President and Chief Energy Specialist, State Grid Energy Research Institute, SGCC, China.

The electricity demand part investigates the economic and business issues based on electricity consumption. Electricity consumption is positively correlated with production output. On the level of firm production, it studies the output such as product quantity, product sale, value added, and production profit by analysing electricity consumption for any production line and other economic activities. For commercial service, it helps managers to analyse revenue, value added, profits, and other business issues based on electricity consumption. On sector level, it studies the production on the basis of electricity consumption. On national level, it reviews macroeconomic developments by analysing electricity consumption on the industrial and state levels.

Production functions with electricity are principles of electricity demand economics. Since increasing volume of products are being produced and increasing amount of electricity is consumed, the product quantity can be mathematically expressed as a function of electricity consumption. Production functions with electricity can be used with electricity consumption as input production function which can be studied on firm level, sectoral level and national level [Hu and Hu (2013)].

Electricity demand economics can be helpful to review, study, observe and analyse economic operation, the trend of economic growth, and the characteristics of the economy's dynamics. For firm production function with electricity, the *e*-*q* function can show the relationship between electricity consumption *e* and product quantity *q*, *e*-*re* function studies the relationship between electricity consumption and revenue *re*, *e*-*v* function demonstrates the relationship between *e* and value added *v*, and *e*-*pf* function shows the relationship between *e* and profit *pf*. Similarly, there are *Es*-*Q* function, *Es*-*Re* function, *Es*-*V* function, and *Es*-*Pf* function on sectoral level. For three industries (primary industry, secondary industry, and tertiary industry), there are E_1-V_1 function, E_2-V_2 function, and E_3-V_3 function to study the electricity consumption and value added for the three industries respectively. For state, there is *E*-*GDP* function to study the relationship between GDP (gross domestic product) and electricity consumption *E* to exhibit the inherent character of the national economy. Electricity demand economics is a new area which has not been explored broadly. Details are discussed in the book "Electricity Economics: Production Functions with Electricity" Springer (2013).

Why do we investigate electricity demand economics? Electric energy, as an important production factor, has been widely used in almost all economic activities (except transportation by gas/oil vehicles and etc.). The characteristics of electricity data of being accurate, accessible and representative of production factors are key elements for electricity demand economics. With the development of electrification, it is also essential in our residential life. In the modern society, commercial business and manufacturing activities are closely associated with electricity consumption. An electric pump can help farmers to irrigate agricultural land; machines and electric equipment require electric power to drive production line in manufacturing; shops, hotels, and restaurants must use electricity to do their daily businesses and services. With the improvement of electric vehicle technologies, transportation will also use more and more electric energy in the near future.

Electricity economics is used to study the issues in the electric power sector based on the principals of economics, which is now being recognised as electricity supply economics. On the other hand, electricity consumption reflects the economic issues of the electricity, which is now recognised as electricity demand economics.

Therefore, electricity economics consists both electricity supply economics and electricity demand economics, i.e. [Hu and Hu (2013)].

Electricity economics = electricity supply economics + electricity demand economics

2. CHARACTERISTICS OF ELECTRICITY DATA

Since electricity is very difficult to be massively stored, it is required that the electric power generation and electricity consumption must be balanced simultaneously. Any unbalance between power supply and demand will make the power system operation unstable, and then power outage could happen at large scale. If the electricity supply is interrupted, not only the production of various industries, but also the people's life would be disrupted. Power system consists of generators, transformers, power lines, power users, etc. In order to guarantee a stable power system operation, the following equation has to hold:

Power generation = line loss + power consumption … … … (1)

Electricity data can be collected and measured by electric meters. With the development of metering technologies, it is easy to access electricity data. For example, China's official electricity data of the month is published in the middle of the next month. It has only two weeks of lag period on monthly basis. However, the GDP data is published quarterly during the year. Furthermore, electricity data obtained from meters contains the features of highly comprehensive, reliable, accurate, and timely data, not merely in China but also in Pakistan as well as many other countries in the world.

With technology innovation, smart grid will highly integrate the system of power grid beyond the boundaries of countries. Smart meters will secure electricity data classification to be more detailed. It is possible to get the data after each 15 minutes. Thus, smart grid and related improvements of technologies will provide more detailed and reliable data on electricity consumption at any time interval. Based on the rule of power system operation, electricity data is more accurate than any other economic data.

National electricity consumption (referred to as total electricity consumption), is the sum of primary industry electricity consumption, secondary industry electricity consumption, tertiary industry electricity consumption, and the residential electricity consumption. Electricity consumption from the three industries can produce value added, which is called productive electricity consumption. To summarise: the productive electricity consumption has four characteristics as follows [Hu and Hu (2013)]:

(1) Necessity—almost any production must use electricity.
(2) Accuracy—the data of electricity consumption can be collected by reading meters. It is objective and unbiased, and it can also be checked by formula (1).
(3) Accessibility—it is very easy to get the reading of electricity consumption from a smart meter per hour (or per 15 minutes).
(4) Representativeness—as a production input, electricity consumption is in proportion to the other production inputs. Electricity consumption can be the representative of all other production factors.

3. PRODUCTION FUNCTIONS WITH ELECTRICITY [Hu and Hu (2013)]

Production function is the relationship between the input and output. What is production function with electricity? The characteristics of electricity data are useful to production function with electricity, i.e. electricity as an input to set up a production function. The characteristic of necessity makes it possible to set up production function for almost all production lines in industries. Representativeness makes it possible to set up the production function with only one production factor, electricity. Therefore, the production function will be very simple and accurate.

The enterprise production function with electricity can reflect both the technology level and management level of the production. If the quantity of product in a firm increases/decreases, it means that the contribution of other production factors also increases/decreases, then, electricity consumption will increase/decrease accordingly as well. The change in electricity consumption is the result of the changes in the other production inputs. Therefore, electricity consumption *e* will vary accordingly with respect to the change in other production inputs (*l*,*m*,…*w*). Relationship between the production inputs (*l*, *m*,…, *w*) and electricity consumption *e* can be seen as a mapping *f* [Hu and Hu (2013)]. It is the positive correlation between *e* and (*l*, *m*,…, *w*). The production function with electricity can be expressed as follows [Hu and Hu (2013)]:

$$y = F(e) \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

The output *y* is the function of input *e*. In fact, the data history and data samples have shown that the formula (2) is a linear function, it can be expressed as follows [Hu and Hu (2013)].

$$y = ae + b \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

where *a* is the slope of the linear function and *b* is the intercept of the function.

As introduced in [Hu and Hu (2013)], the average output of electricity *ay* for enterprise is equal to total quantity of the output *y* divided by the electricity consumption *e*. Marginal output of electricity *my* is the increase in total quantity of the output Δy that results from one-unit increase in electricity consumption Δe.

We can see that the slope of the linear function (3) is the marginal output of electricity.

The output *y* can be total quantity of the product *tq*, revenue *re*, value added *v*, and profits *pf*. for the firm. As discussed in the book "Electricity Economics: Production Functions with Electricity" Springer (2013), we can have the following four production functions with electricity :

$$e\text{-}q \text{ function: } tq = a_1 e + b_1 \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (4)$$

$$e\text{-}re \text{ function: } re = a_2 e + b_2 \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (5)$$

$$e\text{-}v \text{ function: } v = a_3 e + b_3 \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (6)$$

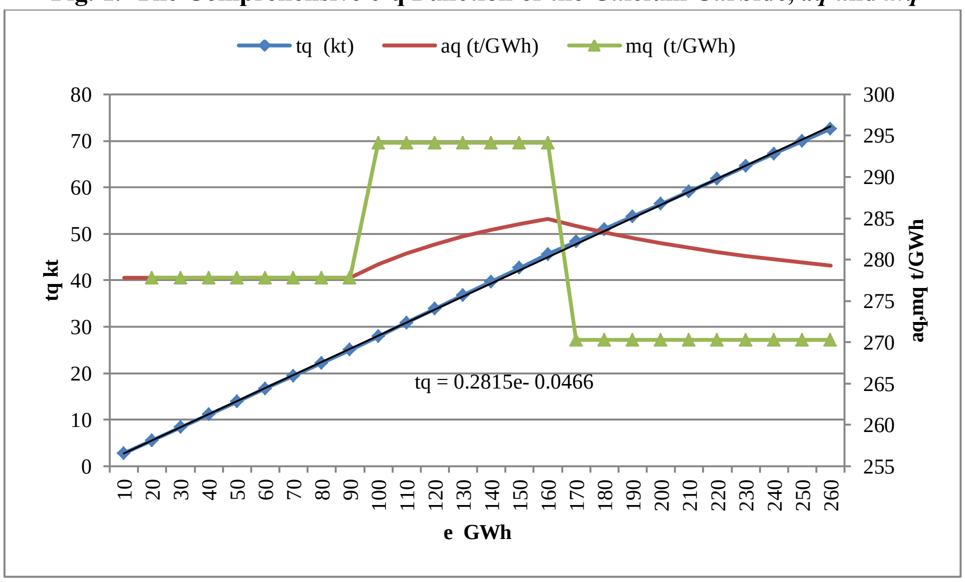
$$e\text{-}pf \text{ function: } pf = a_4 e + b_4 \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (7)$$

A case study is shown in Figure 1 [Hu and Hu (2013)], an enterprise has three types of production lines (calcium carbide furnaces) to produce calcium carbide, the electricity consumption is about 3600kWh per ton of producing calcium carbide with little difference between the three kinds of production lines. The comprehensive *e-q* function for this enterprise is a linear function as follows:

$$tq = 0.2815e - 0.0466 \quad 10 \le e \le 260 \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (8)$$

Figure 1 also shows the curves of the production function with electricity *e-tq*, average quantity of electricity *aq* and marginal quantity of electricity *mq* for the product calcium carbide in this enterprise. The marginal product of electricity varies at electricity consumption 90 GWh and 160 GWh since the three production lines switched one by one. The highest *mq* is 294 ton/GWh, the lowest one is 270 ton/GWh, and the comprehensive *mq* of the three production lines is 281.5 ton/GWh. The *aq* increases from 277.7 ton/GWh to 284.92ton/GWh, and then falls to 279.3 ton/GWh. It increases generally since the intercept of the linear *e-q* function (8) is negative.

Fig. 1. The Comprehensive e-q Function of the Calcium Carbide, *aq* and *mq*



Source: Hu, Zhaoguang and Zheng Hu (2013) *Electricity Economics: Production Functions with Electricity*. p. 41 Springer.

Now we look at the sectoral production functions with electricity, a sector consists of many firms producing the same kinds of product. If we take *Q* as the total quantity of all firms produced product, *Re* as the sectoral revenue, *V* as the value added of the sector, *Pf* as the profit, and *Es* as electricity consumption of all firms, then, sectoral production functions with electricity are as follows:

Es-Q function: $Q = A_1 Es + B_1 \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (9)$

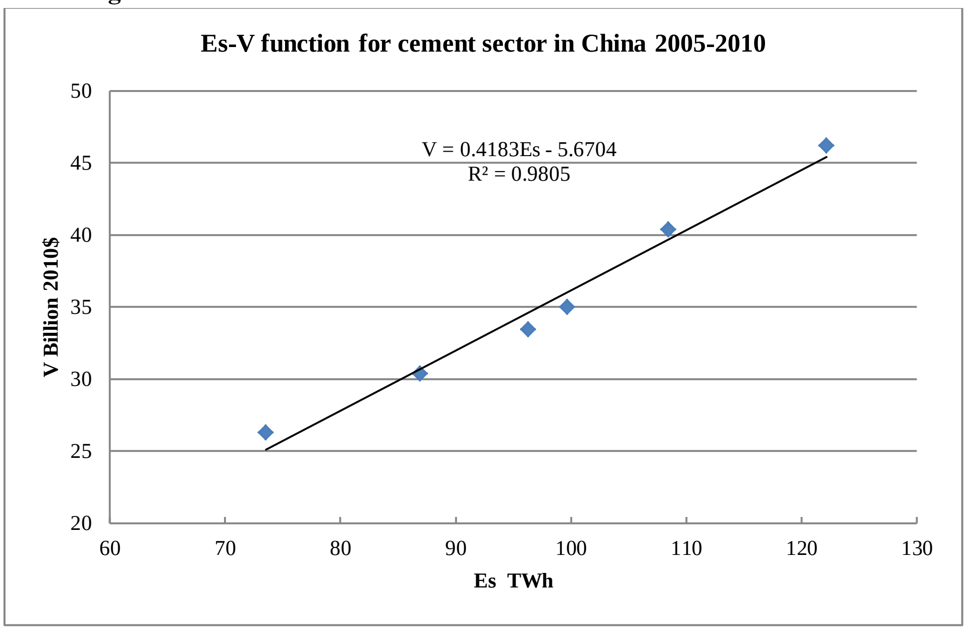
Es-Re function: $\mathrm{Re} = A_2 Es + B_2 \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (10)$

Es-*V* function: $V = A_3 Es + B_3$ … … … … … (11)

Es-*Pf* function: $Pf = A_4 Es + B_4$ … … … … … (12)

Figure 2 shows the *Es*-*V* Function for the cement sector in China during 2005–2010. It is a linear function with the slope as 0.4183 and intercept as –5.6704. It shows that the marginal value added of electricity in the sector is 0.4183$/kWh (in constant 2010 USD) while the average value added of electricity is increasing with the growth of electricity consumption in the cement production.

Fig. 2. *Es*-*V* Function for the Cement Sector in China from 2005 -2010



Source: Hu, Zhaoguang and Zheng Hu (2013) *Electricity Economics: Production Functions with Electricity*. [M] p. 73 Springer.

An industry consists of many sectors, and there are three industries as primary industry (agriculture), secondary industry (industry) and tertiary industry (commercial). The electricity consumption for the three industries can be expressed as E_1, E_2 and E_3, and the value added as V_1, V_2 and V_3 respectively. Then, the production functions with electricity at industrial level can be expressed as follows:

E_1-V_1 function: $V_1 = A_1 E_1 + B_1$ … … … … … (13)

E_2-V_2 function: $V_2 = A_2 E_2 + B_2$ … … … … … (14)

E_3-V_3 function: $V_3 = A_3 E_3 + B_3$ … … … … … (15)

As an example for China, the E_1 was 23.815TWh and the V_1 was 1110.79 billion RMB (in constant 2010 RMB) in 1986. In 2010, they were 97.6TWh and 4053.36 billion RMB respectively. the E_1–V_1 function is a linear function as:

$$V_1(E) = 36.42E_1 + 272.5 \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (16)$$

It shows the marginal value added of electricity in agriculture is 36.42RMB/kWh, and the average value added of electricity is decreasing with increasing electricity consumption.

For secondary industry in China in 1986-2010, the E_2 was 364.19TWh and V_2 was 1198.495 billion RMB in 1986. In 2010, the E_2 was 3145TWh and V_2 was 12567.44 billion RMB. We can see that the growth of E_2 was higher during the period since China's economy is in the different stages of the industrialisation. The E_2–V_2 function is a linear function as follows:

$$V_2(E) = 6.09E_2 - 21.81 \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (17)$$

Its slope is 6.09, and its intercept is -21.81. The marginal value added of electricity of China's secondary industry is 6.09 RMB/kWh, which is lower than that of agriculture. The average value added of electricity is increasing with the growth of electricity consumption since the intercept of the function is negative.

For tertiary industry in China, the E_3 was 31.75TWh and V_3 was 1192.045 billion RMB in 1986. In 2010 the E_3 reached at 447.TWh and $V_3(S)$ was 17308.7 billion RMB. The E_3-V_3 is shown as:

$$V_3(E) = 39.48E_3 - 186.1 \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (18)$$

The slope is 39.48, i.e. MV_3 is 39.48 RMB/kWh. It is higher than MV_2 and MV_1. The AV_3 is increasing with the growth of electricity consumption since the intercept is negative.

On the national level, the production function with electricity is *E-GDP* function as shown below:

$$GDP = AE + B \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (19)$$

The average GDP per unit of electricity is:

$$AGDP = \frac{GDP}{E} \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (20)$$

It is also the electricity intensity of GDP. The marginal GDP per unit change in electricity is:

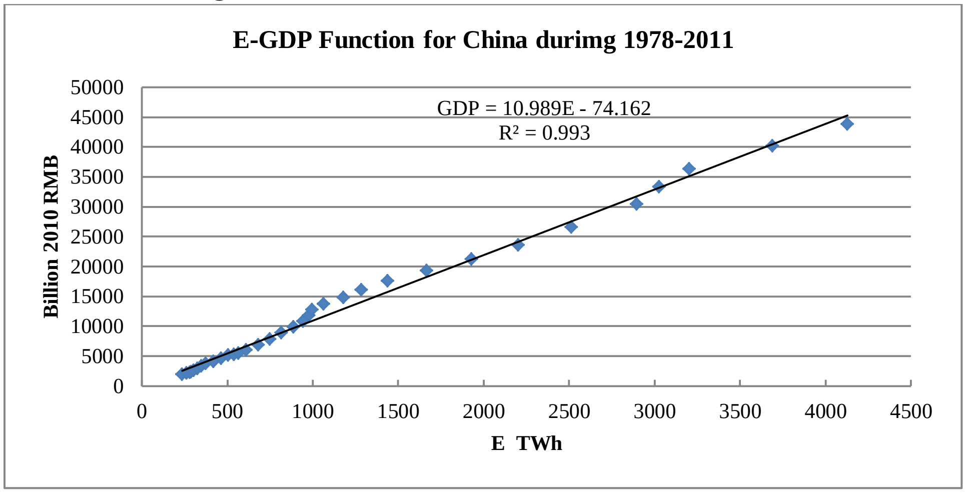
$$MGDP = \frac{\Delta GDP}{\Delta E} \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (21)$$

China is the second biggest economy in the world. As the biggest developing county, its experience of the economic operation would be useful for other developing countries. What is the relationship between *E* and *GDP*? China's *E-GDP* function is (see Figure 3):

$$GDP = 10.989E - 74.162 \qquad 300<E<4000 \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (22)$$

It shows the marginal GDP of electricity in China is 10.989RMB/kWh, and the average GDP of electricity is increasing with the growth of electricity consumption.

Fig. 3. *E-GDP* Function in China from 1978 to 2011



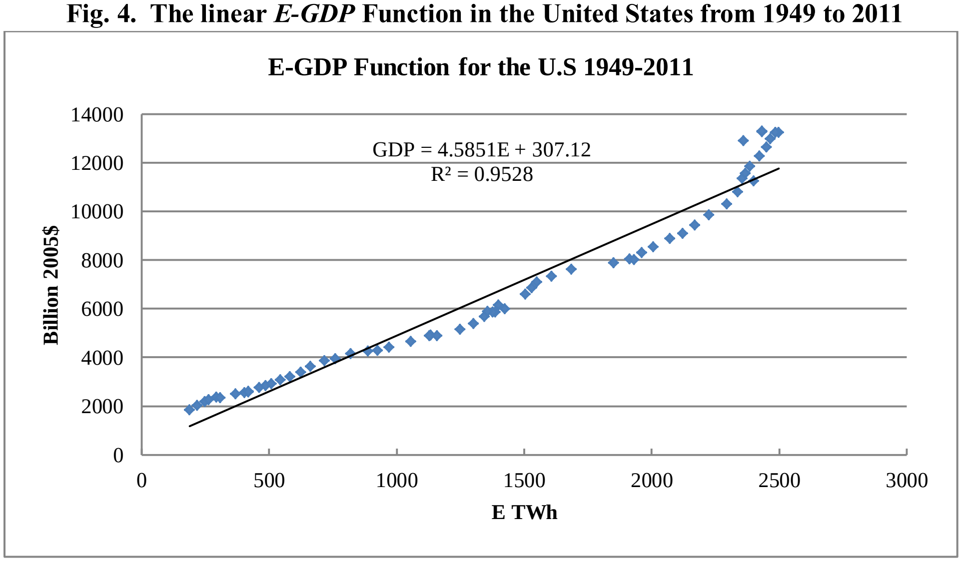
Source: Hu, Zhaoguang and Zheng Hu (2013) *Electricity Economics: Production Functions with Electricity*. [M] p. 144 Springer.

What about the U.S.? The U.S is the biggest economy and the biggest developed country in the world. The *E-GDP* function for the U.S. during 1949-2011 is shown in Figure 4 as:

$$GDP = 4.5851E + 307.12 \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (23)$$

The slope of the function is 4.5851, i.e. the marginal GDP of electricity is 4.5851\$/kWh in constant 2005\$. The intercept is positive , it means the average GDP of electricity is decreasing with the growth of electricity consumption.

Fig. 4. The linear *E-GDP* Function in the United States from 1949 to 2011



Source: Hu, Zhaoguang and Zheng Hu (2013) *Electricity Economics: Production Functions with Electricity*. [M] p. 157 Springer.

Why the R^2 is only 0.9528 in Figure 4? In the past 50 years, the technologies have been greatly improved in the U.S. It has made some changes for the slope and intercept of the *E-GDP* function. The technology innovation has also divided the economic development period. As studied in the paper "Production Function with Electricity Consumption and Its Application" Energy Economics 39(2013) p. 317, there are four periods as 1949-1975, 1975-1987, 1987-1994, and 1994-2011 in the U.S. The *E-GDP* functions for the four periods are as follows:

1949-1975:

$$GDP = 3.1945E + 1342.6 \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (24)$$

1975-1987:

$$GDP = 5.762E - 2018.7 \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (25)$$

1987-1994:

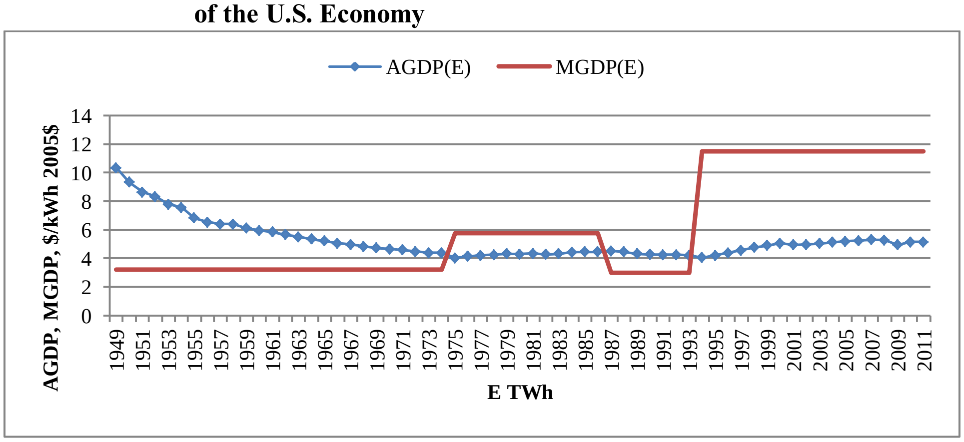
$$GDP = 2.9765E + 2477.2 \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (26)$$

1994-2011:

$$GDP = 11.492E - 15438 \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (27)$$

We can see that the slope of the *E-GDP* function has changed in the periods. It was 3.1945 during 1949-1975 increased to 5.762 in 1975-1987, and decreased to 2.9765 in 1987-1994, then, it increased to 11.492 in 1994-2011. The intercept also changed accordingly with the change of the slope. It was 1342.6 in the period of 1949-1975, and decreased to –2018.7 with the increase of the slope in 1975-1987, and increased to 2477.2 with decrease of the slope in 1987-1994, and then decreased to 15438 with the slope increase sharply in 1994-2011. Figure 5 shows that if the intercept is positive, then, the marginal GDP of electricity will be less than average GDP of electricity, and the AGDP is decreasing with the rise of electricity. On the other hand, if the intercept is negative, then, the marginal GDP of electricity will be bigger than average GDP of electricity, and the AGDP is increasing with the rise of electricity.

Fig. 5. *AGDP* and *MGDP* with the Improvements of Technologies of the U.S. Economy



Source: Hu, Zhaoguang and Zheng Hu (2013) *Electricity Economics: Production Functions with Electricity*. [M] p. 190 Springer.

Japan as the third biggest economy and second biggest developed country in the world, could show the way of industrialisation and post-industrialisation process during 1965-2010. Japan's *E-GDP* function is:

$$GDP = 689.4E + 21546 \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (28)$$

Its marginal GDP of electricity is 689.4 yen/kWh due to the low value of the yen currency. The average GDP of electricity is decreasing with the growth of electricity consumption. In fact, we can see the slope and intercept behave differently in different periods due to the technology innovation. Detail discussion can be found in the book "Electricity Economics: Production Functions with Electricity" in chapter 6 published by Springer (2013).

4. CASE STUDY FOR PAKISTAN

The economist Hollis B. Chenery had studied the characteristics of per-capita income during the different economic stages as shown in Table 1. Per-capita GDP was 783.3 USD (in constant 2005 USD) in 2011 in Pakistan (see Figure 6) [www.worldbank.org]. Accordingly, Pakistan is a developing country in the primary products phase based on Table 1.

Table 1

The Division Standard of Economic Development Phases (Chenery's Model)

Development Phase		Per Capita Income (in 1982 US Dollars)	Per Capita Income (in 2008 US Dollars) [Jiahai, *et al.* (2008)]
Primary Products Stage		260—364	
		364—728	710-1420
Industrialisation Stage	Early	728—1456	1420-2841
	Middle	1456—2912	2841-5682
	Late	2912—5460	5682-10654
Developed Economy Stage		5460—8736	10654-17046
		8736—13104	17046-25569

Source: Hu, Zhaoguang and Zheng Hu (2013) *Electricity Economics: Production Functions with Electricity*. [M] p. 228 Springer.

Based on the GDP, the value of per capita income must be transferred to a particular year's value, and also to USD with exchange rate or purchasing power parity. It will produce some errors. Electricity consumption per capita can show the economic development. Since electricity consumption has positive correlation with GDP, per capita electricity consumption can be taken as a rule for judging the stages of economic development. Therefore, electricity consumption per capita and residential electricity consumption per capita can be used to show the economic development stages (Table 2).

Table 2

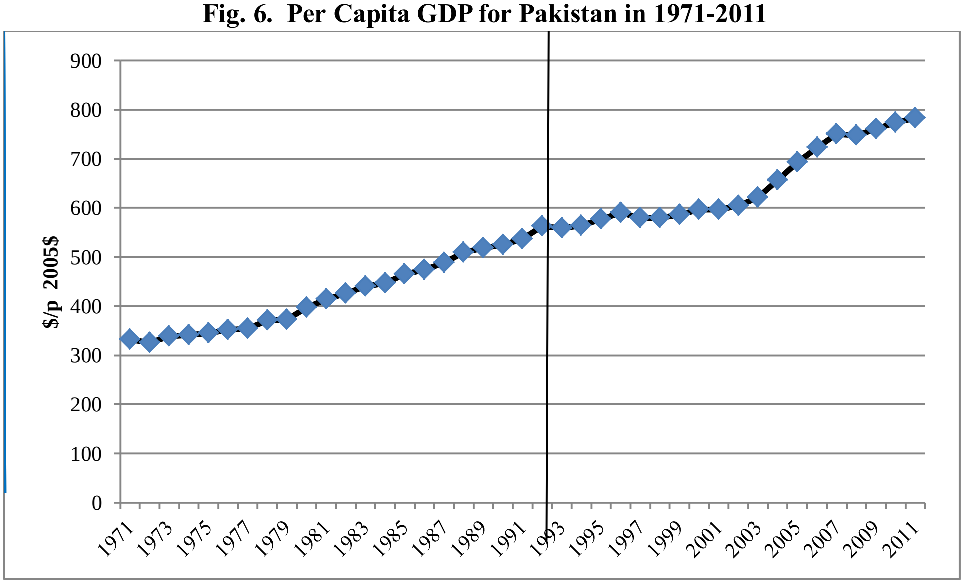
Electricity Consumption Features in Different Economic Development Phases (Unit: kWh/Person)

Development Phase		Per Capita Electricity Consumption	Per Capita Residential Electricity Consumption
Stage of Primary Commodity		<300	<20
	Early	300—1000	20—80
Industrialisation Stage	Middle	1000—2400	80—240
	Late	2400—4500	240—810
Stage of Industrialisation Completion		4500—5000	810—900
Developed Economic Stage	Early	5000—6000	900—1500
	Middle	6000—8000	1500—2400
	Late	>8000	>2400

Source: Hu, Zhaoguang and Zheng Hu (2013) *Electricity Economics: Production Functions with Electricity*. [M] p. 232 Springer.

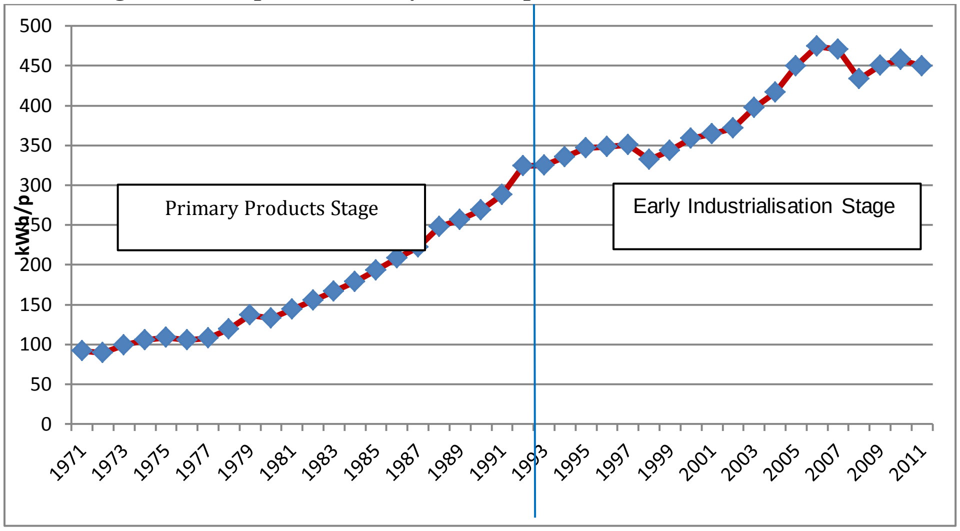
The per capita electricity consumption was less than 300kWh before 1992 (see Figure 7), and then, it was in the interval [300,500]. Since it is difficult to get the data of residential electricity consumption, the per capita electricity consumption would be only index in our study. Based on Table 2, the economy of Pakistan was in the primary product stage before 1992, and then, it entered into the early stage of the industrialisation.

Fig. 6. Per Capita GDP for Pakistan in 1971-2011



Data Source: http://www.worldbank.org.

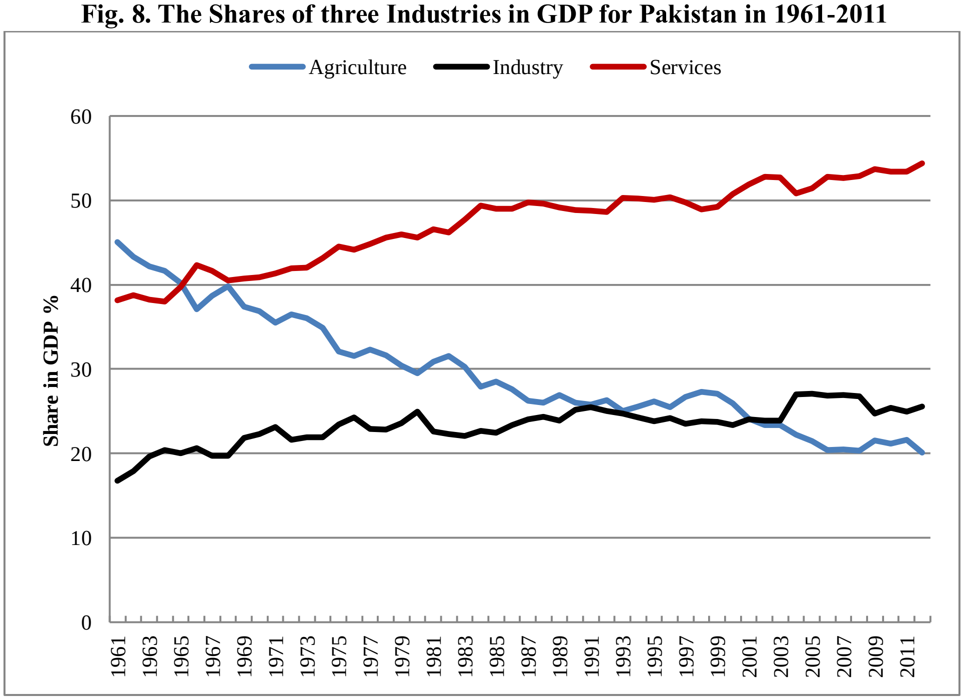
Fig. 7. Per Capita Electricity Consumption for Pakistan in 1971-2011



Data Source: http://www.worldbank.org.

At the early stage of industrialisation, the share of tertiary industry in GDP would be higher than that of secondary industry, and the share of secondary industry would be higher than that of primary industry. It can be shown in Figure 8 that the share of secondary industry is close to that of primary industry in 1991.

Fig. 8. The Shares of three Industries in GDP for Pakistan in 1961-2011



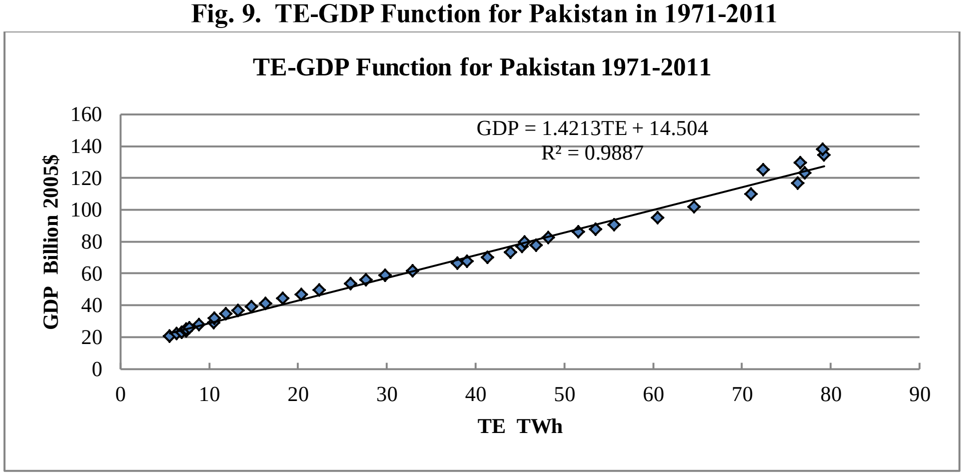
Data Source: http://www.worldbank.org.

Since there is no data on residential electricity consumption, the total electricity consumption is used to set up production function with electricity as *TE-GDP* function. the *TE-GDP* function of Pakistan as shown in Figure 14 is as follows.

$$GDP = 1.4213TE + 14.504 \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (29)$$

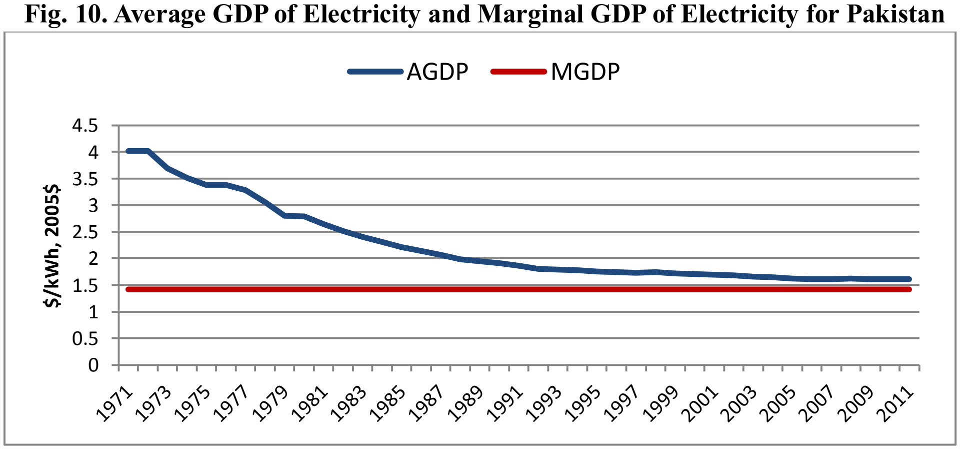
The intercept is 14.504 $/kWh in constant 2005$. The positive sign of the intercept would make the average GDP of electricity greater than marginal GDP of electricity and the AGDP will decline. We can see from Figure 10 that the AGDP (1.6046 $/kWh) was very close to MGDP (1.4213 $/kWh) in 2011. May be the *TE-GDP* function will have a change (mutation) that the slope would increase and the intercept would have negative value. In this case, the average GDP will rise with the more electricity demand in the near future. Some factors will push it such as the secondary industry growth, the drop in the share of primary industry and the technology innovation and improvement. Therefore, we find that there is a great opportunity for the development of Pakistan's economy in the near future to enter the middle stage of the industrialisation.

Fig. 9. TE-GDP Function for Pakistan in 1971-2011



Data Source: http://www.worldbank.org.

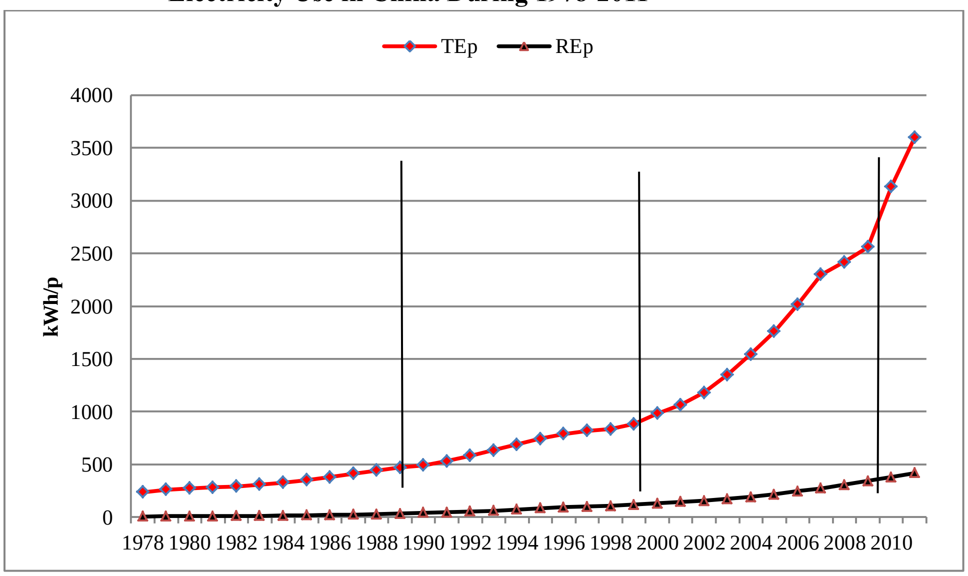
Fig. 10. Average GDP of Electricity and Marginal GDP of Electricity for Pakistan



In order to capture the opportunity of the economic development in Pakistan, what economic growth rate will be in the next 20 years? And what electricity demand will be to meet the economic growth? The forecast of the economic development and electricity demand is very hard since there will be so many uncertainties in the future. However, it is very important to do that since the construction of power plant will take many years. In this paper, the China's experience in the middle stage of the industrialisation will be considered.

The per capita electricity consumption (*TEp*) was 469kWh in 1989 in China, and it was higher than 1000 kWh in 2000 when China entered into the middle stage of the industrialisation. From 2009, China entered into the late stage of the industrialisation since the *TEp* was higher than 2400kWh. The *TEp* growth was 6.53 percent per annum in 1989-1999, and it was 11.23 percent per annum in 1999-2009 in China. The growth rate of *TEp* in the middle stage was higher than that of early stage of the industrialisation (see Figure 11).

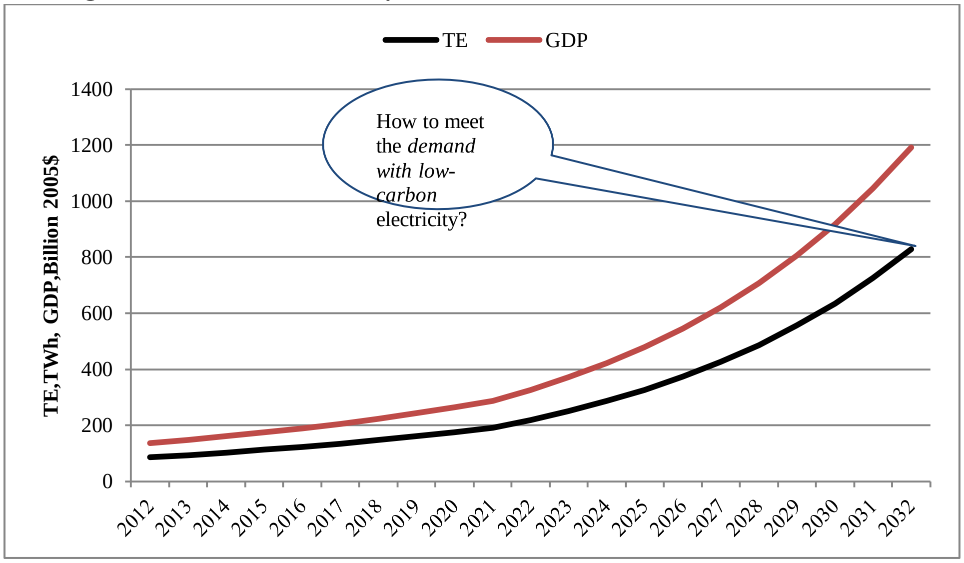
Fig. 11. Per Capita Electricity Consumption and Per Capita Residential Electricity Use in China During 1978-2011



Source: Hu, Zhaoguang and Zheng Hu (2013) *Electricity Economics: Production Functions with Electricity.* [M] p. 244 Springer.

Per capita electricity consumption was 450 kWh in Pakistan in 2011. It was the case of China in 1989. Suppose growth of *TEp* in Pakistan in 2012-2022 will be similar to Chinese' growth of *TEp* at 6.53 percent in 1989-1999, and it will be 11.23 percent in 2022-2032. And also suppose the growth of population in Pakistan will be 2.7625 percent annually until 2032, which is same growth as in 1961-2012. Then, the *TE* will be 219.39 TWh and GDP will be $362.32 billion (in constant 2005$) in 2022. In 2032, the *TE* will be 827.9 TWh and GDP will be $1191.19 billion in Pakistan (see Figure 11). How to meet the electricity demand with low-carbon electricity? The power planning method will be important in the model of low-carbon electricity.

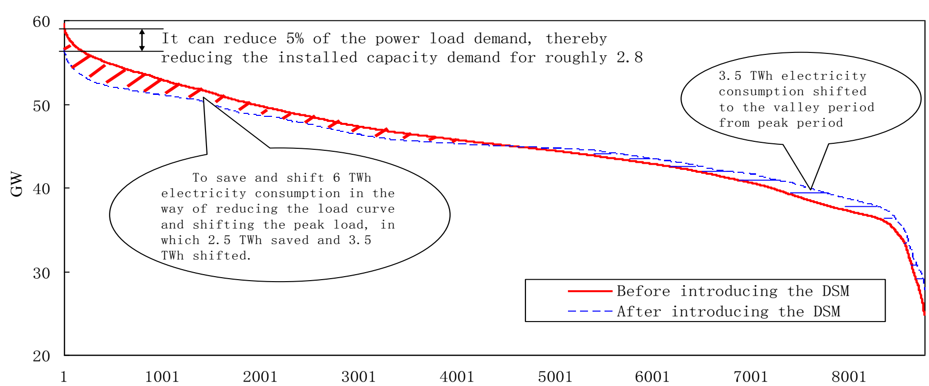
Fig. 12. Outlook of Electricity Demand and GDP for Pakistan in 2012-2032



5. INTEGRATED RESOURCE STRATEGIC PLANNING (IRSP)

Power generation expansion planning should meet the long term electricity demand for economic growth. However, since the energy resource is limited and the issue of climate change motivates increasing level of energy efficiency. Power demand side management (DSM) is one of the most important measures in the world. The key of DSM is to design various kinds of business management programmes for different power customers to affect their behaviour on electricity use. DSM is a useful tool for shifting peak load and saving energy. There is a case study of DSM in Figure 13. The peak load is 58 GW as shown in Figure 13. By designing some DSM projects, the peak load can be reduced by 5 percent, which is 2.8 GW. DSM projects also move 3.5 TWh from peak hours to off peak hours and it could save 2.5 TWh.

Fig. 13. The Energy Saving and Peak Load Shifting by DSM

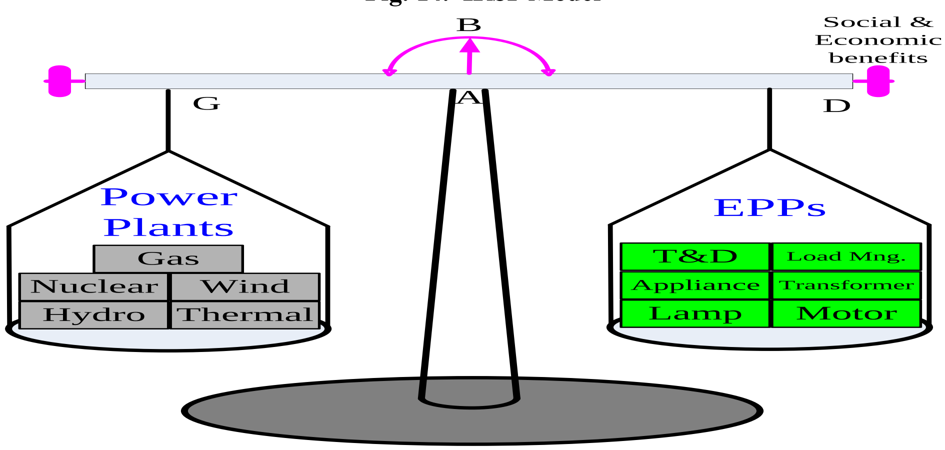


Source: Hu, Zhaoguang and Zheng Hu (2013) *Electricity Economics: Production Functions with Electricity*. [M] p. 18 Springer.

In order to involve DSM in power planning, it has to play the same role as a power plant in the planning model, and hence Efficient Power Plant (EPP) has been studied [Hu, Han, and Wen (2013)]. Lighting EPP is a lot of high efficiency lamps to reduce the load and save electricity. For example, one 10W of high efficiency lamp is the same with 50W ordinary lamp, thus, it saved 40W to replace the ordinary lamp by efficiency lamp. What about 1 billion high efficiency lamps? It will save 4GW. Therefore, 1 billion 10W efficiency lamp is same as a 4GW power plant. It is a 4GW EPP. And also there are motor EPP, transformer EPP and so on.

Integrated Resource Strategy Planning (IRSP) is a power planning model to meet the electricity demand by building all kinds of power plants such as coal-fired power plant, hydro power plant, nuclear power plant, wind power plant, gas power plant, solar power plant, and EPPs (see Figure 14). The goal of the IRSP model is to maximise social and economic benefits including lower investment and lower emissions. The government can design policy incentives to promote EPP and renewable power generation by formulating some rebate and incentive policies. Thus, the IRSP model is also a useful tool for policy study in the power planning.

Fig. 14. IRSP Model



Source: Zhaoguang Hu, Quan Wen, Jianhui Wang, Xiandong Tan, Hameed Nezhad, Baoguo Shan, Xinyang Han: Integrated Resource Strategic Planning in China, [J] *Energy Policy* 38(2010), p. 4636.

In order to show the impact of IRSP model, a case study for China can be an example since there is no data for Pakistan. In 2012, the total power generation capacity was 1167.75 GW as shown in Table 3, and the electricity consumption was 4959 TWh. It is forecasted that the electricity demand will be 7734 TWh in 2020 [Hu, Tan, and Xu (2013)]. In order to meet the demand and promote EPP, the power plants and EPPs have been studied by IRSP model as shown in Table 3. In 2020, the total power generation capacity will be 1805.94 GW. The coal-fired power plant is only project to increase 165.77 GW, while solar power will increase 146.72 GW and wind power will increase 159.17 GW in the next 8 years. EPPs will share 197.65 GW in 2020. Total electricity saving will be 388.3 TWh, more than 1280.79 million tons of coal equivalent will be saved. The CO_2 emission will be reduced more than 3163.63 million tons.

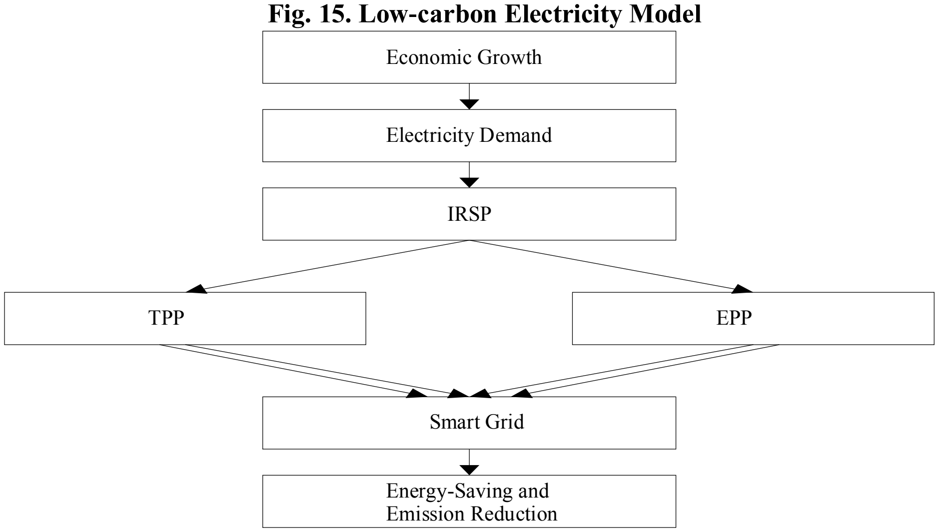
Table 3

Power Plants and EPP by IRSP for China in 2020

Generation Capacity (GW)	2020	2012
Generation Capacity	**1805.94**	**1167.75**
Hydro	**350**	248.90
Coal-fired	**975.94**	819.17
Nuclear	**60**	12.57
Wind	**200**	60.83
Gas	**70**	23.00
Solar	**150**	3.28
Epps	**197.65**	
Lamp	**37.65**	
Motor	**30**	
Transformer	**30**	
Frequency	**20**	
Appliance	**20**	
Interrupt Load	**60**	
Electricity Saving (TWh)	**388.3**	
Coal Saving （Mtec)	**1280.79**	
CO2 Saving (Mt)	**3163.63**	

The scenario of low-carbon electricity can be shown in the Figure 15. With the growing economy, the electricity demand will also experience a high growth. There are two ways to meet the electricity demand. One is to build more power plants and another way is to build more EPP. It is clear that EPP will be the first priority to meet the electricity demand. It can be achieved by providing policy incentives to promote EPP.

Fig. 15. Low-carbon Electricity Model



Source: Hu, Zhaoguang, Jiahai Yuan, Zheng Hu (2011) Study on China's Low Carbon Development in an Economy-Energy-Electricity-Environment Framework. [J] *Energy Policy* 39, p. 2602.

On the other hand, Pakistan is facing power shortage. It will harm the economic growth. However, DSM will play an important role to mitigate the power shortage in peak hours. Load management, demand response, the tariff at time of use, and many other technologies are useful to reduce/shift the peak load. For example, there were power shortages around 30GW-50WG in China in 2003-2006, DSM has been used in China then, and it did not harm the economic growth badly.

6. CONCLUSIONS

Based on the above discussions, this paper has the following conclusions;

(1) Electricity economics consists of electricity supply economics and electricity demand economics. Production functions with electricity are the principles of electricity demand economics. Integrated resource strategic planning is a part of electricity supply economics. Low-carbon electricity can be recognised as the planning of IRSP and the implementation of smart grid in the economic development.

(2) Pakistan's economy is in the early phase of industrialisation according to the per capita electricity consumption. China's economy is in the late phase of the industrialisation. Experiences and lessons from China's economic development would provide references to Pakistan.

(3) Low-carbon electricity will be an important economic development model in the near future. It is suggested to study how to make economic development with low-carbon electricity in Pakistan to avoid the mistakes from other countries.

(4) DSM and IRSP will not only play an important role in low-carbon electricity, but also will be important and useful measures to deal with power shortage in Pakistan.

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Comments

First of all, I congratulate the speaker for presenting such an interesting paper on a topic of utmost importance for Pakistan. Chinese economy has grown at a wonderfully high rate for past several decades and has successfully surmounted the associated challenge of providing energy resources needed to support this growth. As Pakistan aspires to attain high growth rate in future, and at the same time, is facing an acute energy crisis, our policy makers and researchers stand to learn a great deal from Chinese experience.

Economics is a vast subject but it can be summarised in two simple words, 'demand' and 'supply'. It is in this light that the paper examines various aspects of electricity economics. The paper presents various production functions that express output as a linear function of electricity alone. As indicated in the paper, this approach has several advantages. While it is extremely difficult to obtain reliable and accurate data on various inputs and the output in a short period of time, electricity data can be read almost instantaneously from an electricity meter.

It needs to be stressed that this remarkable simplification of the production function comes at a cost. One of the assumptions needed for this simplification, that electricity is used in every production process, seems harmless given the state of technology today. However, a more stringent assumption is also required to give electricity its 'representativeness', hence enabling us to express output as a function of just electricity. We need to assume that all other inputs are used in a fixed proportion to electricity. This, nonetheless, leaves no room for substitutability between inputs. If this assumption is close to reality, it does no harm to the estimation of the production function. Instead of counting the number of steel toed shoes used by the workers, we are counting pairs of shoes, and in doing so we are along the expansion path. Whether this is actually the case in the real world is a question that needs to be decided empirically.

If output is a linear function of electricity, then simple mathematics shows that marginal output is a horizontal straight line, whereas average output per unit of electricity is a rectangular hyperbola. This can be seen from relevant equations in the paper as well. Therefore, some further elaboration is needed to explain why some figures in the paper do not show strict conformity to these geometric forms.

The worthy speaker has very imaginatively used his approach of expressing national income as a function of electricity to redefine Chenery's stages of economic development. Chenery expresses these stages in terms of per-capita income. Using Dr Hu's electricity production function, the per-capita income figures can be readily translated into per-capita electricity consumption figures. Now we don't have to go through the trouble of deciding on the base year, converting figures into U.S dollar equivalent, worrying about the purchasing power parity issues and finally waiting for at least a quarter to get GDP figure. Determining a country's stage of development is now just an electricity meter away. But these are not the only reasons I like this new measure. One more reason for my liking for Dr Hu's measure is that whereas Chenery's measure puts Pakistan in the primary products phase, the lowest stage of economic development, Dr Hu's measure puts us in the early stage of industrialisation.

Najam us Saqib

Pakistan Institute of Development Economics,
Islamabad.

Comments

Let me first thank Dr Musleh ud Din and Dr Durr-e-Nayab for extending an invitation to be a discussant for this paper. I would also like to take this opportunity to congratulate PSDE for organising a conference on 'energy', an important issue facing Pakistan.

At the outset, let me make it clear that my comments are not a criticism of the research presented in this paper but to share my thoughts to further expand this research.

It is an interesting paper, presenting a theoretical application of 'electricity economics' and its empirical application. I commend Dr Zhaoguang and Dr Zheng to combine economics, ecology and engineering in one paper. The main contribution of this paper is to develop a simple production function including electricity as an input and analysing its impact on economic growth using data from China and Pakistan. While the paper is comprehensive, it is relatively weak in economic theory and modelling. The paper uses a simple linear production function. Its empirical part, analysis on China is quite strong but not so for Pakistan. This is perhaps due to non-availability of data in case of Pakistan.

The use of energy as an input in the production function is not new in economics literature. The debate on whether energy should be used as an input in the production function goes back to Neo-classical and classical economists such as Adam Smith, David Ricardo, John McGulloch, John Stuart Mill, and so on. Nicholas Gorgeson-Roegen (1972, 1976) was perhaps the first one to identify the absence of energy in economic theory in a formal way which later led to the development of ecological economics.[1] Economics literature identifies two channels through which energy (or electricity) enters the production function. One, primary converting activities (PCAs) which convert energy from natural resources (such as solar, heat, light, wind, running water, tide, minerals, fossil fuels, gravitation, and chemicals) into forms that will eventually be used to produce goods and services. Second, secondary converting activities (SCAs) which do not make any direct contribution of energy to the economy. The paper focuses mainly on PCAs. I believe that authors may carefully look into the following issues to further improve this paper.

- The paper uses a simple linear model (a Cobb-Douglas production function). There are better ways to formulate production function such as CES, etc. Authors may want to explore these.
- The paper uses electricity as exogenous. Literature suggests that electricity is determined by energy consumption and other variables. This may have an impact on the results obtained in this paper. Electricity can also be taken as a function of capital use. The paper correctly differentiates between different sectors but still assumes electricity as exogenous.

[1]Please also see Zaeske (2012), Chaudhry (2010) and Filippini and Pashauri (2002) for more details in the context of Pakistan and India.

– The above leads to another question—whether capital and electricity are substitutes or compliments. As discussed in some papers at this conference; it seems appropriate to consider the two as compliments in case of Pakistan. The literature, however, is indecisive on this issue. This also depends on 'rebound effect', which means that the improvement in technical efficiency of energy use is expected to reduce energy consumption. For example, engineering literature shows that a 20 percent improvement in fuel efficiency for passenger cars could lead to a 20 percent reduction in motor fuel consumption per personal automotive. This is also consistent with some results presented in this paper.

I would also like to make some suggestion for designing and implementing policies to conserve energy. This could be achieved through the cooperation and coordination of public and private sector in Pakistan should focus:

- Governance is the main issue in energy problems in Pakistan. This should be the priority in our policy planning.
- As stated by Abid Sulari (a guest speaker at this conference), we need to control and minimise electricity waste. In a country facing severe energy shortage, we should maximise our use of natural energy. Businesses should operate during daylight. I strongly feel that market should operate between 8am to 8pm.
- We should find ways (as used in many countries) to preserve water (preserve rain water by having rain water tanks) and use alternative ways of electricity generation such as solar.
- Research and development (R&D) to improve the efficiency of electricity use.
- The paper talks about carbon tax. But this is a major political issue even in developed countries.

Finally, let me suggest that the paper presented by Dr Zhaoguang offers an interesting research agenda. I believe with the expertise of Dr Zahoguang and the level of economic expertise available at PIDE, this could result in broader research collaboration between the two institutions under the guidance of Dr Zhaoguang.

Thank you very much.

Ahmed M. Khalid

Bond University,
Australia.

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