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The Role of Renewable Energy Supply and Carbon Tax in the Improvement of Energy Security: A Case Study of Pakistan

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1. INTRODUCTION

As energy is a vital element for sustained economic growth and development, therefore energy consumption is used as a basic indicator of people's living standards. Due to technological and industrial development, the demand of energy in Pakistan is increasing more than the total primary energy supply; therefore, it is confronting the severe energy deficit today. So there should be a serious concern for the government about the energy security and should take actions for the development of indigenous alternative and renewable energy resources.

Renewable portfolio supply (RPS), and carbon tax are the two indirect policy options used for the improvement of energy security. Renewable Energy Promotion is used to reduce greenhouse gas emission, promote local energy sources and improve energy security through reducing energy dependency and diversification of energy sources. Carbon tax is an indirect policy option for energy security enhancement through emission reduction. Imposing tax on carbon emission will alter the primary energy supply mix, more efficient fuel and technologies will be substituted for less efficient fuel and technologies. This will reduce the primary energy demand and lead to improved energy security.

Energy security, particularly security of oil supply, has become a key political, and economic issue in recent years. Energy security in simple words means the security of energy supply. From economic point of view, energy security refers to the provision of reliable and adequate supply of energy at reasonable prices in order to sustain economic growth.

Pakistan as an energy deficient country is facing the challenge of energy security. A few papers analysed this issue highlighting just the energy situation of the country, ignoring the analytical side of the issue. Sahir and Qureshi (2007) gave an overview of the energy security issues in the global and regional perspectives and presented the specific implications and concerns for Pakistan. Moreover, the global and regional energy

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security is not vulnerable to shortage of energy resources but may be exposed to energy supply disruption, non-availability of tradable resources and threatened by growing terrorism and geopolitical conflicts.

Due to limited fossil fuel resources and poor economy, a huge portion of the population in Pakistan still have no access to modern day energy services such as electricity [see Mirza, *et al.* (2003); Mirza, *et al.* (2007a); Mirza, *et al.* (2007b)]. To overcome energy shortage, Pakistan should develop its indigenous fossil energy resources and alternative renewable resources such as mini-hydro, solar and wind resources [see Mirza, *et al.* (2007a); Mirza, *et al.* (2007b)]. Pakistan has a vast potential of mini-hydro, solar and wind energy resources, the exploitation of these resources could produce a enough electricity, which could be provided to the northern hilly areas and the southern and western deserts. This will help in reducing dependency on fossil fuels imports and also improve energy security.

Pakistan recorded a shortfall of 40 percent between demand and supply of electricity in 2008 [see Asif (2009)]. To overcome this shortfall, Pakistan has many sustainable energy options including hydro, biomass, solar, and wind resources. The total estimated hydropower potential is more than 42 GW and so for only 6.5 GW has been utilised. Although biomass is another conventional resource of energy in Pakistan but still it is not commercialised. Solar and wind options are also identified as potential energy resources but still these are not in operation on a vast scale.

This paper is aimed at analysing the effects of policies of renewable portfolio supply (RPS), and carbon tax on diversification of energy resources, technology mix in energy supply side and demand side; energy efficiency and energy conservation; and energy security during the planning horizon 2005-2050. A MARKAL-based model for an integrated energy system of Pakistan was developed to accomplish the research.

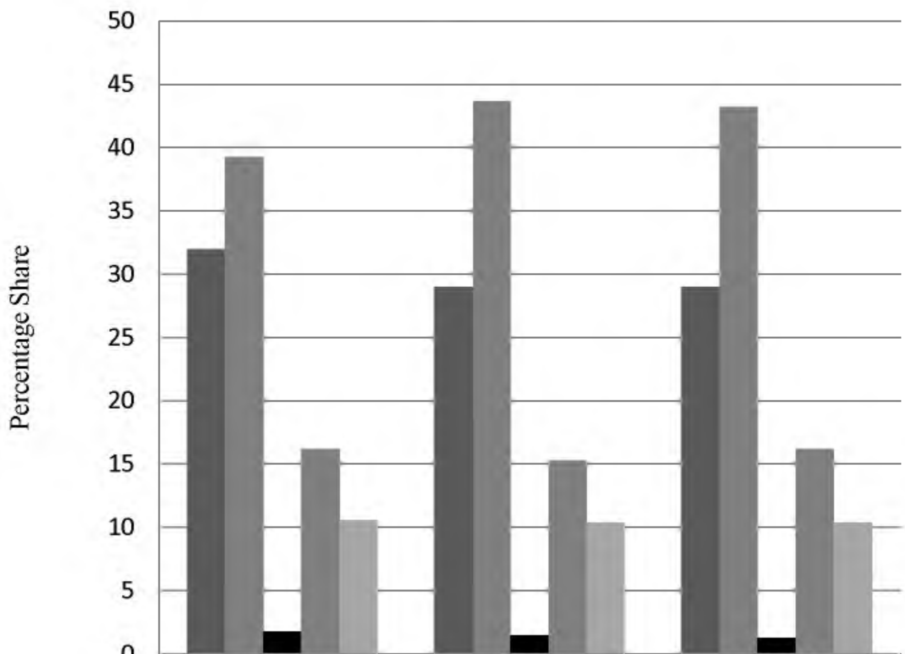
The paper is structured as follows. Section 2 gives an overview of Pakistan energy outlook. Section 3 provides the methodology and model formulation. Section 4 gives a brief description of the scenarios while analysis of the base case, renewable portfolio supply case and carbon tax case is given in Section 5. Finally, Section 6 presents the main conclusions.

2. PAKISTAN ENERGY OUTLOOK

Pakistan energy sector consists of electricity, gas, petroleum and coal. Oil and gas are major contributors to the Pakistan's primary energy supply mix. (Fig. 1.) The primary energy supply mix of Pakistan consists of 78 percent oil and gas, 13 percent hydro, 8 percent coal and 1 percent nuclear (see Pakistan Economic Survey, 2006-07). The most interesting feature of Pakistan's primary energy supply mix is that share of oil decreases from 32 percent in 2005-2006 to 29 percent in 2010-2011, and share of gas increases from 39 percent in 2005-2006 to 43 percent in 2010-2011, while the shares of other resources remained almost constant over the same period. It shows that Pakistan energy sector is switching from oil to gas and other resources.

Pakistan indigenous oil production meets only one-sixth of the current oil demand while imports one-third of the total energy demand. This implies that Pakistan is unable to meet energy demand from its internal resources, and is a net importer of energy.

Fig. 1. Primary Energy Supply Mix (2005-2010)



	2005-06	2008-09	2010-11
Oil	32	29	29
Gas	39.3	43.7	43.2
LPG	1.8	1.5	1.3
Electricity	16.2	15.3	16.2
Coal	10.6	10.4	10.4

Source: Pakistan Economic Survey 2011-12.

Historical data shows that Pakistan has been dependent on oil imports from the Middle East since it came into being. The crude oil imports for the year 2005-06 were about 8.56 mtoe as compared to local production of crude oil of 3.24 mtoe and the imports of petroleum products were about 5.85 mtoe. The cost of all these oil and petroleum products was equivalent to US$ 4.6 billion, which is roughly equal to 25-30 percent of the total import bill. This huge import bill put enormous pressure on the economy [Pakistan (2005)]. On the other hand, the primary energy demand has increased significantly but the primary energy supply remained at the same level, which created a huge gap between demand and supply. As a result, the country is facing huge energy shortage.

Pakistan imports about 29 percent of total primary commercial energy. Although Pakistan has a variety of energy resources, but approximately 80 percent of the energy supply is from oil and natural gas. The dependence on imported fuels especially on imported oil is likely to increase, which will affect Pakistan's economy adversely. To avoid this negative impact, we should explore opportunities for untapped large renewable energy resources in the form of mini-hydro, solar and wind projects so that Pakistan can fulfil its energy needs and keep up its economic growth.

Table 1 displays the annual trends of primary energy supplies and their per capita availability from 1996-97 to 2005-06, which indicates that the primary energy supply has increased by 50 percent and the per capita availability by 26 percent in the last 10 years.

Table 1

Primary Energy Supply and Per Capita Availability

Year	Primary Energy Supply (Tons of Oil Equivalent)	% Change	Per Capita Availability (Tons of Oil Equivalent)	% Change
1996-97	38.515	–0.6	0.295	–3.0
1997-98	40.403	4.9	0.305	3.3
1998-99	41.721	3.3	0.313	2.7
1999-00	43.185	3.5	0.317	1.2
2000-01	44.404	2.8	0.319	0.6
2001-02	45.068	1.5	0.315	–0.1
2002-03	47.056	4.4	0.324	2.7
2003-04	50.831	8.0	0.341	5.3
2004-05	55.533	9.3	0.363	6.7
2005-06	57.855	4.2	0.372	2.2

Source: Pakistan Economic Survey 2006-07.

3. METHODOLOGY

3.1. Model Formulation

This study makes use of bottom up MARKAL-based least cost energy system model[1] as an analytical framework for the analysis of energy security in case of Pakistan [Loulou, *et al.* (2004)]. It models the flows of energy in an economy from the source of primary energy supply, conversion of primary energy into secondary energy, and finally the delivery of various forms of energy to the end-use services. In the model, these flows of energy are described through detailed representation of technologies providing an end-use demand. Figure 2 shows the simplified structure of the MARKAL modelling framework through reference energy system.

Basically, Pakistan energy system model consists of four modules; primary energy supply, conversion technologies, end-use technologies and demand for energy services. Primary energy supplies are hydro, crude oil, natural gas, imports of oil, nuclear, solar wind etc., while conversion technologies module consists of power generation and transmission systems, oil refineries, natural gas processing and transmission systems. Service energy demand is grouped into five sectors: agriculture, residential, commercial, industrial, and transport sector (see Figure 2).

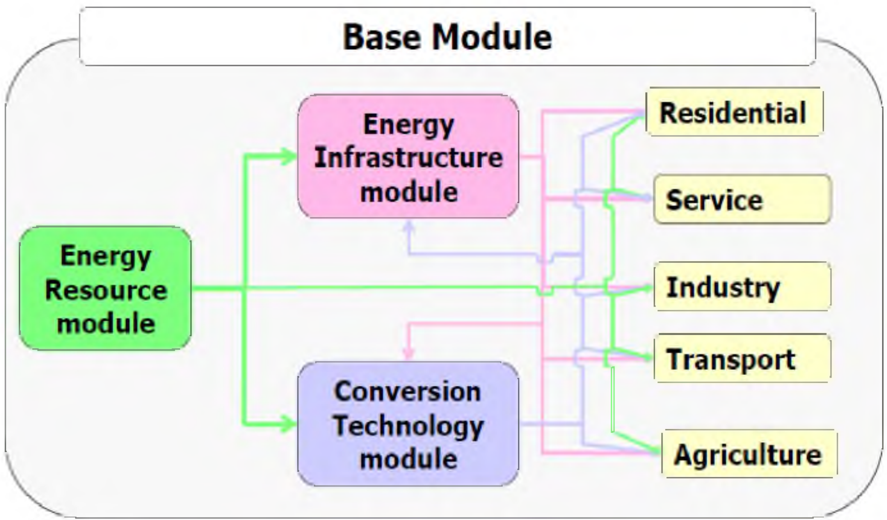
End use demands are a measure of the useful energy output provided by the demand technologies in each end use demand category. It is assumed in MARKAL that

[1]Model formulation is described in Appendix-C.

the essential energy demand is for some service (an amount of cooking or heating), while the basic service is fixed, it can be provided by different mixes of devices and fuels. End-use demand technologies and conversion technologies are described in detail in Appendix A&B.

The objective function of the least cost energy system is to minimise the total discounted cost during the planning horizon; the total cost comprises of capital cost net of salvage value, fuel cost, operation, and maintenance costs. The optimal solution given by the model must satisfy energy demand, capacity and energy demand-supply balance constraints.

Fig. 2. General Reference Energy System



Source: www.ukerc.ac.uk/support/tiki-download_file.php?fileId=951.

3.2. Service Demand Projection

Service energy demand is projected through three different techniques using econometric models as well as using identity relating service energy demand in particular sector to GDP and Value Added of the particular sector. In the econometric approach, the dependent variables are number of energy devices, passenger kilometres, ton kilometres etc. The independent variables are Gross Domestic Product (GDP) and population. The other approaches consider the service demand of particular sector in particular year as dependent on the service demand of sector in base year multiplied by the ratio of the current year GDP and base year GDP; the service demand of particular sector in particular year depends on the service demand of sector in base year multiplied by the ratio of the current year value added and base year value added.

The econometric approach was used to project the service energy demand in transport and residential sectors, while the service energy demand in industrial, commercial and agriculture sectors was projected through economic value added and GDP approach.

Service demand projection for fans, air conditioners and cooking is based on the GDP growth through the following formulation:

$$SD_{i,k,t} = SD_{i,k,0} \times \frac{GDP_t}{GDP_o}$$

Where $SD_{i,k,t}$, $SD_{i,k,0}$ are service demand of sector *i* sub-sector *k*, in year *t* and base year respectively, GDP_t and GDP_0 represent Gross Domestic Product in year *t* and Gross Domestic Product in base year.

Service demand projection for agriculture, commercial and industrial sectors is based on the following formulation:

$$SD_{i,k,t} = SD_{i,k,0} \times \frac{VA_{i,k,t}}{VA_{i,k,0}}$$

Where $SD_{i,k,t}$ is service demand of sector *i* subsector *k* in year *t*, $SD_{i,k,0}$ is service demand of sector *i* subsector *k* in base year, $VA_{i,k,0}$ is the i_{th} sector k_{th} subsector value added in the base year and $VA_{i,k,t}$ is the i_{th} sector k_{th} subsector value added in the year *t*.

Electricity-related service demand and supply were considered in six time slices along with two seasons (summer and winter) and two periods (peak and off-peak) so that the variation of electricity loads on the energy system can be reflected.

3.3. Energy Security Indices

The prime objective of this research is to classify policy options for the improvement of energy security of Pakistan. The fundamental and suitable criterion for the classification of policy options are the calculation of energy security indices for the whole planning horizon 2005-2050. In this study, four energy security indicators are used, i.e. Net Energy Import Ratio (NEIR), Shannon-Wiener Index (SWI), Diversification of Primary Energy Demand (DoPED), Vulnerability Index (VI) and Energy Intensity (EI). These indicators are estimated by using the MARKAL model which is energy-system model depicting long-term development of the energy-system. The indicators are explained as follows:

$$NEIR = \frac{Net\ Imports}{(Domestic\ Production + Net\ Imports)}$$

The value of NEIR close to 1 indicates that the energy system of that country is to a large extent dependent on energy imports.

$$SWI = -\sum_i x_i \ln(x_i)$$

where x_i represents the share of energy supply from each source. A higher value of SWI means well diversified energy sources ultimately leading to improved energy security while a lower value implies low diversification of energy sources and poorer energy security [Grubb, *et al*. (2006)].

$$DoPED = \frac{\sqrt{Coal^2 + Oil^2 + Hydro^2 + Biomass^2 + Other^2}}{Total\ Primary\ Energy\ Demand}$$

Where the value of DoPED close to 1 indicates that the economy is reliant on one energy resource while a value close to zero (0) means that the energy sources in the economy are uniformly spread among several energy resources.

Vulnerability may be linked to strong energy import dependency i.e. it may also be linked to the high level of energy import value in GDP. It refers both to the quantity and cost of energy imports.

$$VI = \frac{EEI}{GDP}$$

where; *EEI* is expenditure on energy import and GDP is Gross Domestic Product.

$$EI = \frac{TPES}{GDP}$$

Where *EI* is Energy Intensity, TPES is Total Primary Energy Supply and GDP is Gross Domestic Product.

4. SCENARIOS DESCRIPTION

Three scenarios were studied: (i) Base case, (ii) renewable portfolio supply (RPS) case, and (iii) carbon tax case. Details of the scenarios are explained as follows.

4.1. Base Case

In this case, Pakistan GDP growth rate was assumed to grow at an annual growth rate of 7.0 percent and the growth rate of population was estimated at an annual growth rate of 1.9 percent based on the GDP and population data for the period of 2000-2013 [Pakistan (2006-07), World Economic Outlook Database (2008)].

Under the base case, the maximum available stock of fossil energy resource (e.g., coal, oil and petroleum products, and natural gas) was estimated as the sum of proven reserve of the resource, its probable reserve and its possible reserve. In the power sector, renewable energy options (hydro, wind, and solar), natural gas-based power plants as well as nuclear power plants were included in the model (see Appendix B). The options considered for the transportation sector include road, water and air transports.

4.2. Renewable Portfolio Supply Scenario

Renewable Energy Promotion is used to reduce emissions, promote local energy sources and improve energy security through reducing energy dependency and diversification of energy sources. To assess the effects of renewable portfolio supply (RPS), we implemented five different constraints and calculated energy security indicators for the whole planning horizon 2005-2050. The constraints are:

(a) **RPS10-** Total renewable based electricity generation is set to be 10 percent of total electricity generation (excluding large hydro) during period of 2005 to 2050.

(b) **RPS20-** Total renewable based electricity generation is set to be 20 percent of total electricity generation (excluding large hydro) during period of 2005 to 2050.

(c) **RPS30-** Total renewable based electricity generation is set to be 30 percent of total electricity generation (excluding large hydro) during period of 2005 to 2050.
(d) **RPS40-** Total renewable based electricity generation is set to be 40 percent of total electricity generation (excluding large hydro) during period of 2005 to 2050.
(e) **RPS50-** Total renewable based electricity generation is set to be 50 percent of total electricity generation (excluding large hydro) during period of 2005 to 2050.

4.3. Carbon Tax Scenario

Carbon tax is an indirect policy option for energy security enhancement through emission reduction. Imposing tax on carbon emissions will alter the primary energy supply mix, more efficient fuel and technologies will be substituted for less efficient fuel and technologies. This will reduce the primary energy demand and lead to improved energy security. To assess the effects of carbon tax on energy security, we implemented different constraints in the model. The constraints are:

(a) **CO_2-10-** Impose a tax of 10US$/t$CO_2$ until 2050.
(b) **CO_2-15-** Impose a tax of 15US$/t$CO_2$ until 2050.
(c) **CO_2-20-** Impose a tax of 20US$/t$CO_2$ until 2050.
(d) **CO_2-25-** Impose a tax of 25US$/t$CO_2$ until 2050.
(e) **CO_2-30-** Impose a tax of 30US$/t$CO_2$ until 2050.

5. ANALYSIS OF THE BASE CASE

Energy system development of Pakistan during the planning horizon of 2005–2050 under the base case is discussed as follows:

5.1. Primary Energy Supply in the Base Case

As can be seen from Figure 3, the primary energy supply in the base case under the renewable portfolio supply scenario shows an increasing trend over the whole planning horizon 2005–2050 indicating the rising energy supply and per capita energy availability. The primary energy supply in Pakistan is found to increase from 2475 PJ in 2005 to 35,559 PJ in 2050. Results from model simulation show that oil and gas are the major parts of primary energy supply in the base case, while coal and renewables are also contributing to primary energy supply. Over the time, primary energy supply mix is changed and the cheap resources (renewables and coal) dominate the primary energy supply mix.

As can be seen from Figure 4, the primary energy supply in the base case under the carbon tax scenario shows an increasing trend over the whole planning horizon 2005–2050. The primary energy supply is estimated to increase from 2475 PJ in 2005 to 22,684 PJ in 2050. Results from model simulation show that oil and gas have major contribution to primary energy supply in the base case, while coal and renewables are also contributing to primary energy supply. Over the time, primary energy supply mix is changed and the cheap resources (renewables) and oil dominate the primary energy supply mix.

Sector wise fuel consumption in both scenarios is presented in Figure 5 and Figure 6. In the renewable portfolio supply scenario, industrial sector, residential sector and transport sector dominate the sectoral fuel consumption in 2005, while the shares of industrial sector and transport sector have increased considerably while the share of residential sector has declined in 2050. Similarly under carbon tax scenario, transport sector holds the largest share in the sector wise fuel consumption followed by industrial sector and residential sector in 2005, while the share of residential sector has declined and shares of transport sector and industrial sector have grown significantly in 2050.

Fig. 3. Primary Energy Supply in Renewable Portfolio Supply Scenario in Base Case

(PJ)

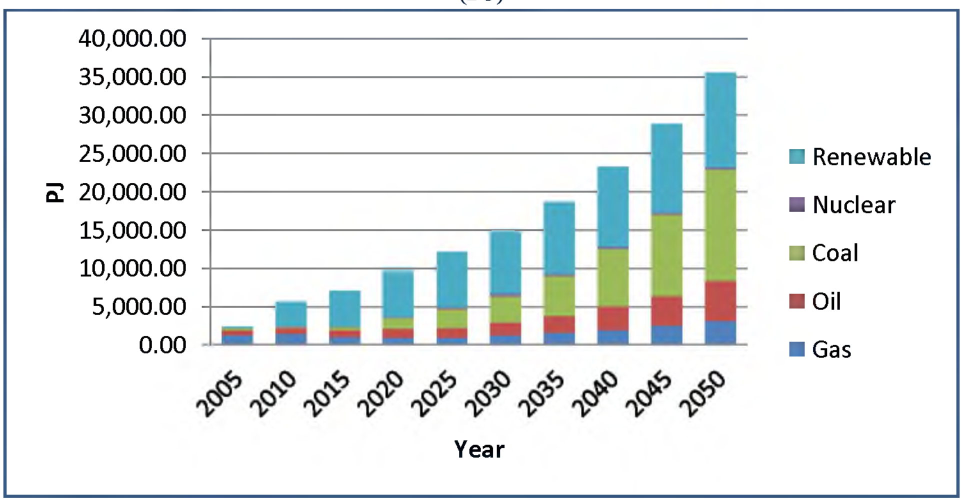


Fig. 4. Primary Energy Supply in Carbon Tax Scenario in Base Case

(PJ)

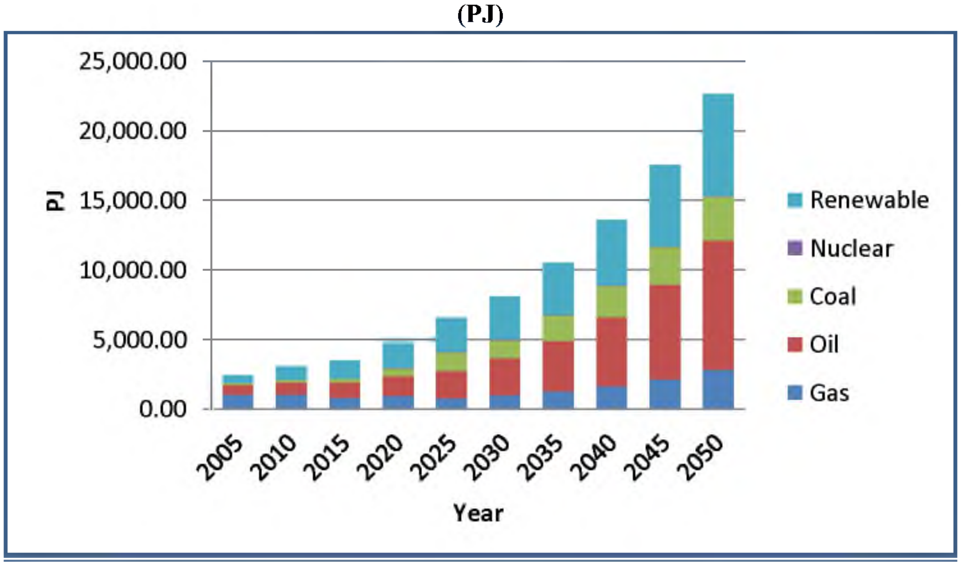


Fig. 5. Sectoral Energy Consumption in Renewable Portfolio Supply Scenario (Percentage Share)

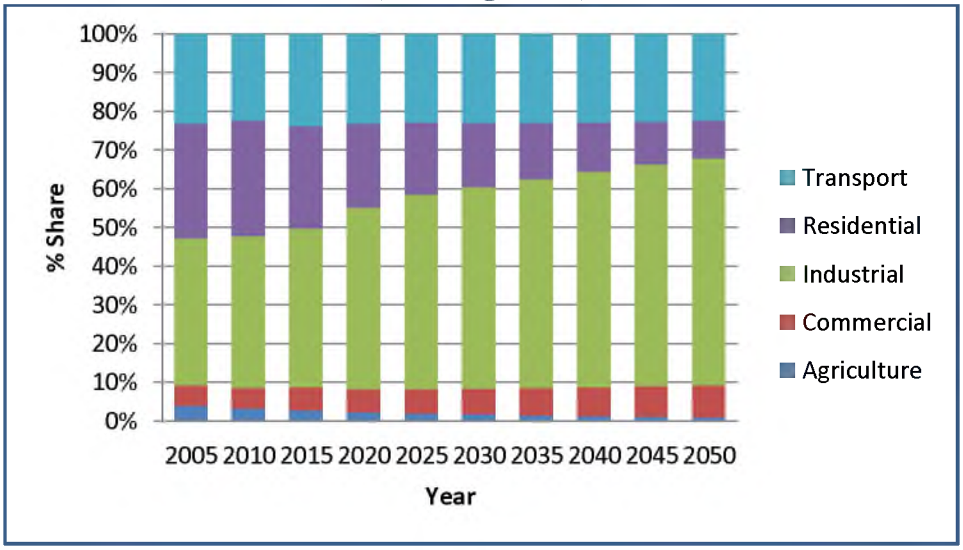
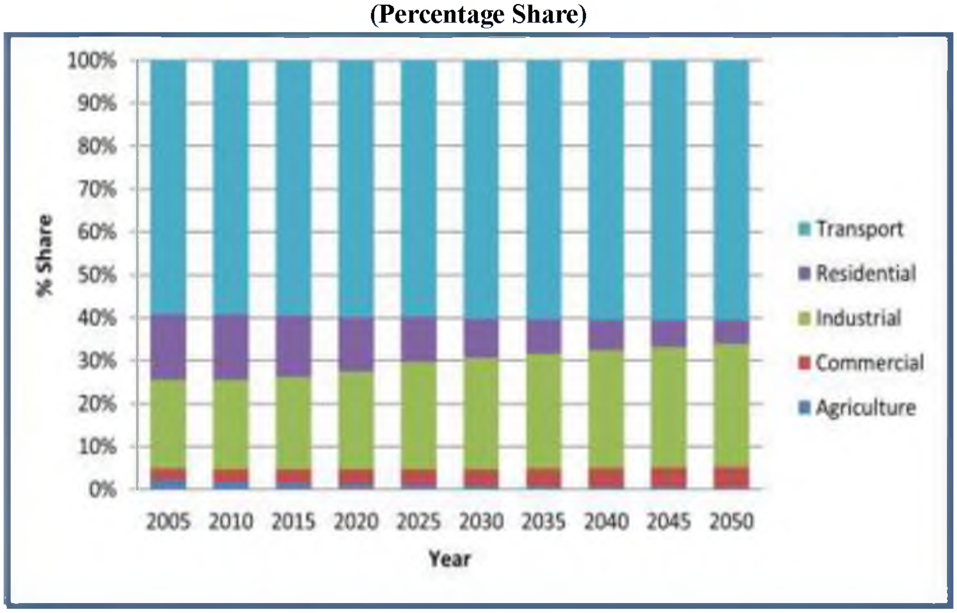


Fig. 6. Sectoral Energy Consumption in Carbon Tax Scenario (Percentage Share)



5.2. Results and Discussion

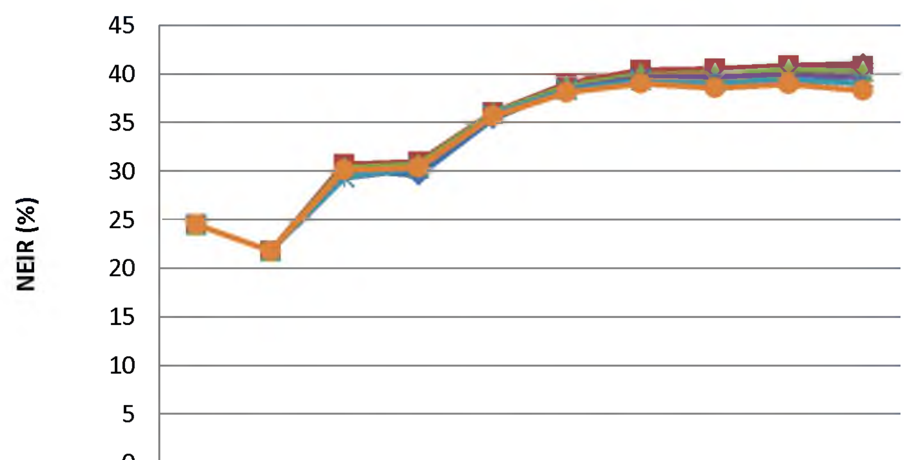
5.2.1. *Energy Security under Renewable Portfolio Supply and Carbon Tax Scenarios*

For the classification of policy options for the improvement of energy security of Pakistan, we imposed five different types of Renewable Portfolio Supply and Carbon Tax constraints (These constraints are briefly explained in section-4.2 and 4.3) in the MARKAL model for Pakistan. On the basis of these constraints, we analysed import dependency, diversification of energy resources, vulnerability, and energy intensity for the whole planning horizon.

5.2.1.1. *Energy Import Dependency under Renewable Portfolio Supply and Carbon Tax Scenario*

Energy Import Dependency is one of the key aspects of energy security that can be calculated as a percentage of net energy imports in total primary energy supply. Energy security indicator based on net energy import ratio (NEIR) is shown in Figure 7 and Figure 8. As can be seen from Figure 7, the net energy imports from the rest of the world indicated by NEIR would increase from 24 percent in 2005 to 41 percent in 2050 under renewable portfolio supply scenario indicating higher energy import dependency, but as more renewable energy resources are exploited and enter in the energy system, the energy import dependency decreases from 41 percent in base case to 38 percent in RPS50 scenario, which is a considerable reduction in energy import dependency. The main factor behind the reduction of energy import dependency is the share of renewable resources based electricity generation in the total electricity generation, which increases significantly as compared to the base case and that is a signal towards energy security improvement in Pakistan.

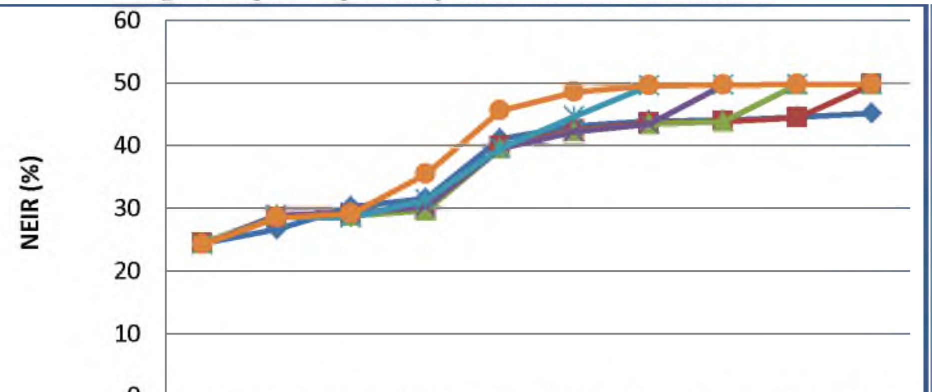
Fig. 7. Import Dependency under Renewable Portfolio Supply Scenario



	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
BASE	24	22	30	30	35	38	40	41	41	41
RPS10	24	22	31	31	36	39	40	41	41	41
RPS20	25	22	30	31	36	39	40	40	40	40
RPS30	24	22	29	30	36	38	40	40	40	40
RPS40	24	22	29	30	36	38	39	39	39	39
RPS50	24	22	30	30	36	38	39	39	39	38

On the other hand, energy import dependency under carbon tax scenario would increase from 24 percent in 2005 to 45 percent in 2050 as shown in Figure 8. Energy import dependency in carbon tax scenario has a mixed trend, but as more and more carbon tax is imposed, import dependency increases. The main reason behind the increased energy import dependency is the increased shares of imported oil in the primary energy supply in 2050 under carbon tax scenario.

Fig. 8. Import Dependency under Carbon Tax Scenario



	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
BASE	24	27	30	32	41	43	44	44	45	45
CT10	24	28	29	30	40	42	44	44	44	50
CT15	24	29	29	30	40	42	43	44	50	50
CT20	24	29	29	30	40	42	43	50	50	50
CT25	24	29	29	31	40	45	50	50	50	50
CT30	24	28	29	35	46	49	50	50	50	50

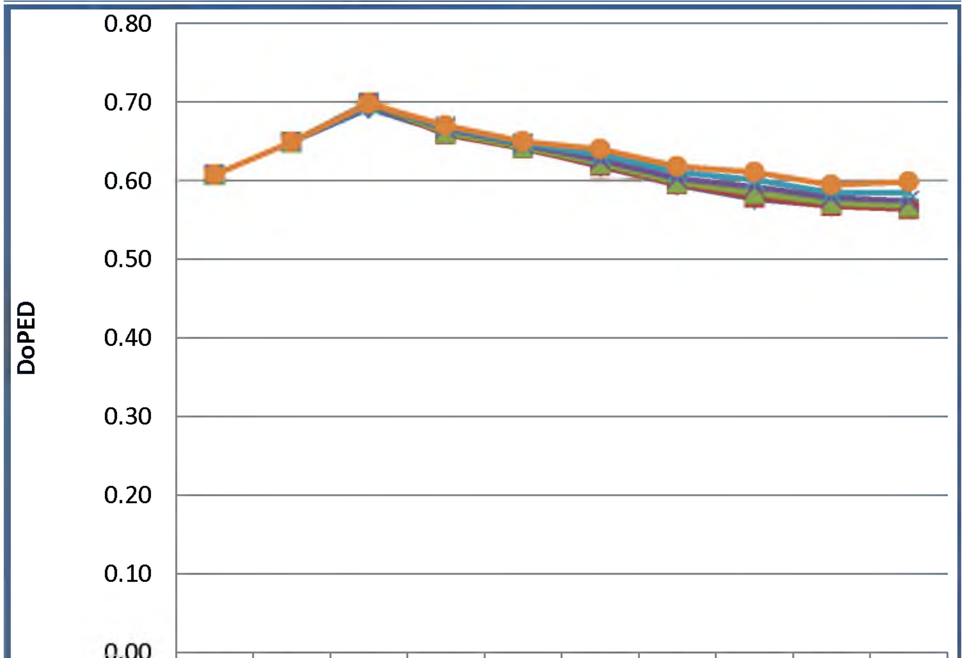
5.2.1.2. *Diversification under Renewable Portfolio Supply and Carbon Tax Scenario*

Diversification of primary energy sources is another important factor of energy security. DoPED and Shannon-Wiener Index (SWI) illustrate the diversification of the primary energy supply mix of the future energy system. As can be seen from Figure 9, the value of DoPED drops from 61 percent in the 2005 to 56 percent in 2050 in the base case implying better diversification among different energy resources under the renewable portfolio supply scenario. Diversification decreases up to 2015 and then in the long run, it increases up to 2050 in all renewable portfolio supply scenarios. On the other hand, diversification under carbon tax scenario reflected somewhat mixed trend (Figure 10). First, diversification of energy resources improves up to 2025 in the base case and then it deteriorates up to 2050. While in case of all carbon tax scenarios, diversification improves up to 2035 and then starts to deteriorate up to 2050.

Diversification can also be examined through Shannon-Wiener Index (SWI); higher value of SWI implies better diversification among different energy resources. Figure 11 and Figure 12 depicts the model simulated values for SWI under the renewable portfolio supply and carbon tax scenarios. As can be seen from Figure 11, the value of SWI increases from 51 percent in the 2005 to 55 percent in 2050 in the base case implying better diversification among different energy resources under the renewable portfolio supply scenario. Diversification index does not perform well up to 2015 and then in the long run, it shows improved performance up to 2050 in all renewable portfolio supply scenarios. On the other hand, diversification under carbon tax scenario demonstrates a mixed trend in different time periods (Figure 12). First, diversification of energy resources improves up to 2025 in the base case and then it drops up to 2050. While in case of all carbon tax scenarios, diversification shows better performance up to 2035 and then starts to worsen up to 2050.

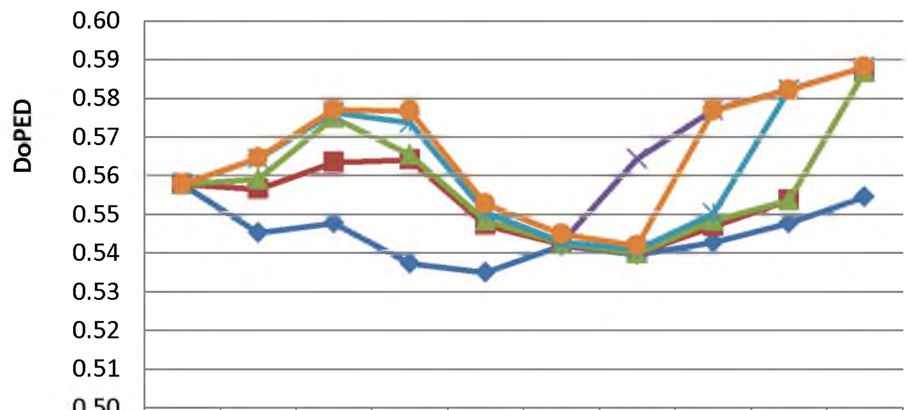
Both the indices ultimately imply better diversification of energy resources by 2035 as compared to 2005 that leads to energy security improvement in Pakistan by 2035.

Fig. 9. Diversification of Energy Resources under Renewable Portfolio Supply Scenario



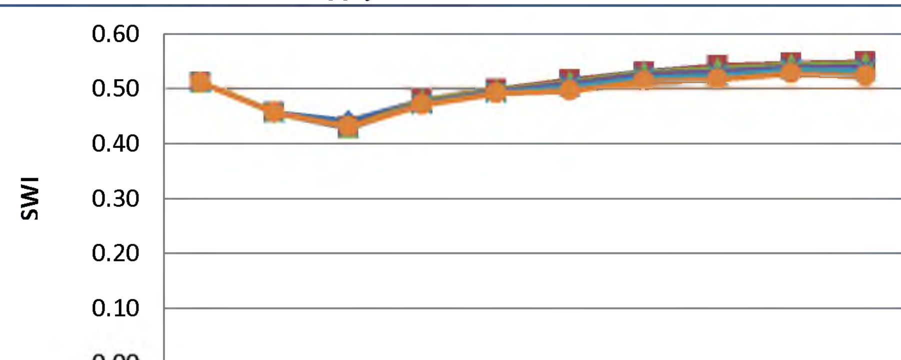
	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
BASE	0.61	0.65	0.69	0.66	0.64	0.62	0.59	0.58	0.57	0.56
RPS10	0.61	0.65	0.70	0.66	0.64	0.62	0.60	0.58	0.57	0.56
RPS20	0.61	0.65	0.70	0.66	0.64	0.62	0.60	0.58	0.57	0.57
RPS30	0.61	0.65	0.70	0.67	0.65	0.63	0.60	0.59	0.58	0.57
RPS40	0.61	0.65	0.70	0.67	0.65	0.63	0.61	0.60	0.58	0.58
RPS50	0.61	0.65	0.70	0.67	0.65	0.64	0.62	0.61	0.59	0.60

Fig. 10. Diversification of Energy Resources under Carbon Tax Scenario



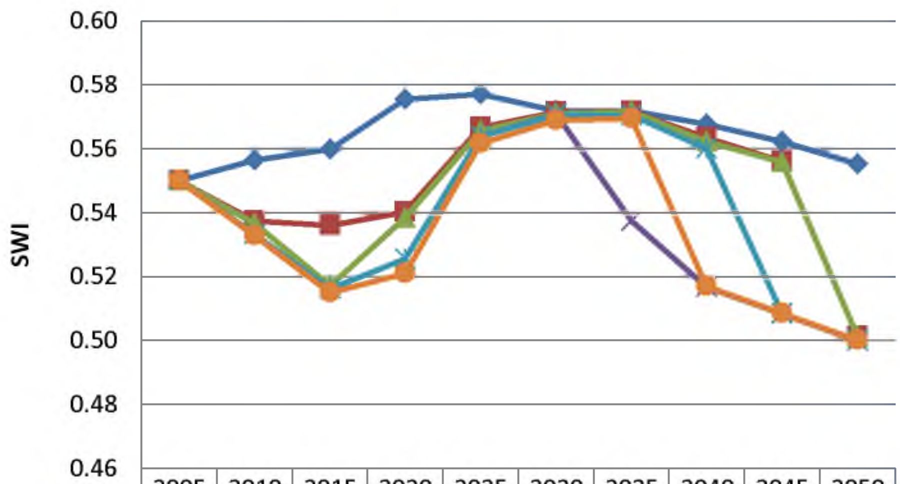
	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
BASE	0.56	0.55	0.55	0.54	0.53	0.54	0.54	0.54	0.55	0.55
CT10	0.56	0.56	0.56	0.56	0.55	0.54	0.54	0.55	0.55	0.59
CT15	0.56	0.56	0.57	0.57	0.55	0.54	0.54	0.55	0.55	0.59
CT20	0.56	0.56	0.58	0.57	0.55	0.54	0.56	0.58	0.58	0.59
CT25	0.56	0.56	0.58	0.57	0.55	0.54	0.54	0.55	0.58	0.59
CT30	0.56	0.56	0.58	0.58	0.55	0.54	0.54	0.58	0.58	0.59

Fig. 11. Diversification of Energy Resources under Renewable Portfolio Supply Scenario



	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
BASE	0.51	0.46	0.44	0.48	0.50	0.52	0.53	0.54	0.55	0.55
RPS10	0.51	0.46	0.43	0.48	0.50	0.52	0.53	0.54	0.55	0.55
RPS20	0.51	0.46	0.43	0.48	0.50	0.51	0.53	0.54	0.54	0.55
RPS30	0.51	0.46	0.43	0.47	0.49	0.51	0.53	0.53	0.54	0.54
RPS40	0.51	0.46	0.43	0.47	0.49	0.50	0.52	0.52	0.53	0.53
RPS50	0.51	0.46	0.43	0.47	0.49	0.50	0.51	0.52	0.53	0.52

Fig. 12. Diversification of Energy Resources under Carbon Tax Scenario



	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
BASE	0.55	0.56	0.56	0.58	0.58	0.57	0.57	0.57	0.56	0.56
CT10	0.55	0.54	0.54	0.54	0.57	0.57	0.57	0.56	0.56	0.50
CT15	0.55	0.54	0.52	0.54	0.57	0.57	0.57	0.56	0.56	0.50
CT20	0.55	0.53	0.52	0.53	0.56	0.57	0.54	0.52	0.51	0.50
CT25	0.55	0.53	0.52	0.53	0.56	0.57	0.57	0.56	0.51	0.50
CT30	0.55	0.53	0.51	0.52	0.56	0.57	0.57	0.52	0.51	0.50

5.2.1.3. *Vulnerability and Energy Intensity under Renewable Portfolio Supply and Carbon Tax Scenario*

The energy security indices NEIR, SWI, and DoPED quantify the physical availability of primary energy supply to the economy ignoring the monetary significance of energy imports. To capture the economic significance of energy imports, we used vulnerability index.

As can be seen from Figure 13, vulnerability under renewable portfolio supply scenario shows a declining trend up to 2020 and then reflects rising trend up to 2050 in the base case as the amount of imports in the total primary energy increase over the time. Under all renewable supply portfolio scenarios, vulnerability index exhibits the increasing trend, however, it declines as more and more renewable energy enters into the system over time. The declining behaviour of vulnerability index (Figure 13) implies that vulnerability will decrease in the long run as compared to short run in all cases that will lead to enhanced energy security of Pakistan under the renewable portfolio supply scenarios.

Under carbon tax scenario, vulnerability decreases up to 2020 in base case as well as in all carbon tax scenarios and then it increases up to 2050 (Figure 14). The main reason for increasing vulnerability is the rising shares of energy imports from the Middle East.

The other energy security indicator such as energy intensity (Figure 15 and Figure 16) is a measure of the energy efficiency of an economy. It is calculated as units of energy per unit of GDP. High energy intensities indicate a high price or cost of converting energy into GDP and low energy intensity indicates a lower price or cost of converting energy into GDP. In case of renewable portfolio supply scenario, energy intensity has a rising trend showing economic inefficiency in the base case (Figure 15), while energy intensity decreases with the inclusion of renewable energy in the system that reflects economic efficiency of the energy system under all renewable portfolio supply scenarios. This is an indication of energy security enhancement in the renewable portfolio supply scenarios.

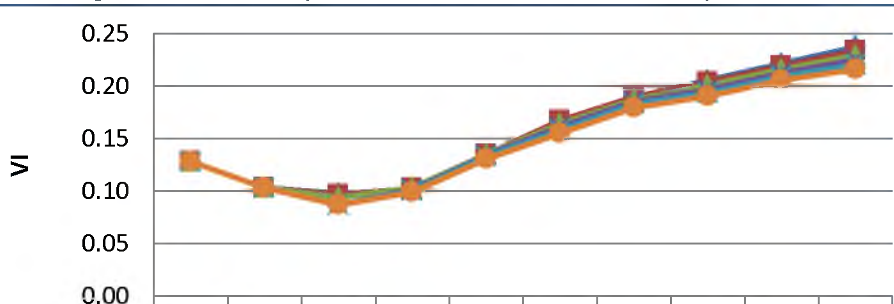
In case of carbon tax scenario (Figure 16), energy intensity decreases up to 2020 in the base case, which is a sign of economic efficiency as more efficient technologies are put in place under carbon tax scenario and after 2020, energy intensity shows a mixed trend up to 2050 in the base case as well as in all carbon tax scenarios.

5.2.1.4. *Green House Gases Emission under Renewable Portfolio Supply and Carbon Tax Scenario*

Environmental emissions are decomposed into green house gases emissions e.g. CO_2, CH_4 CO, SO_2, NO_x, and PM_{10}. According to Figure 17, total cumulative green house gases emissions decrease from 165 million tons in base case to 151 million ton in RPS50 scenario i.e. there is 9 percent reduction in green house gases emissions under renewable portfolio supply scenario, which is quite significant. As can be seen from Figure 18, total cumulative greenhouse gases emissions is reduced from 72 million tons in base case to 19 million ton in CT30 scenario, which is a significant reduction in greenhouse gases emissions under carbon tax scenario.

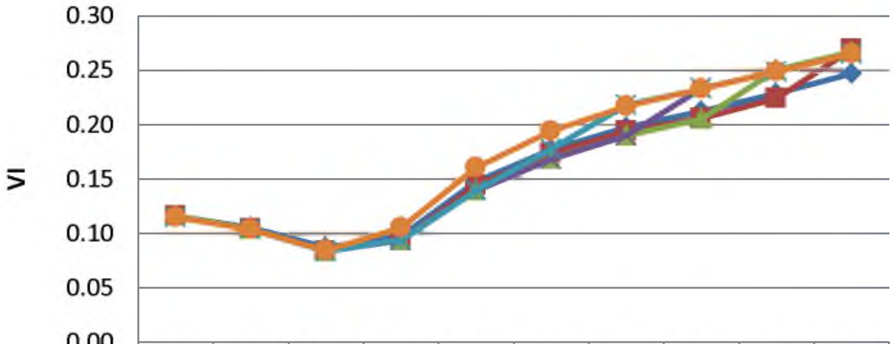
All these facts imply that renewable portfolio supply and carbon tax policies can be used as combined policy options for the enhancement of energy security in case of Pakistan.

Fig. 13. Vulnerability under Renewable Portfolio Supply Scenario



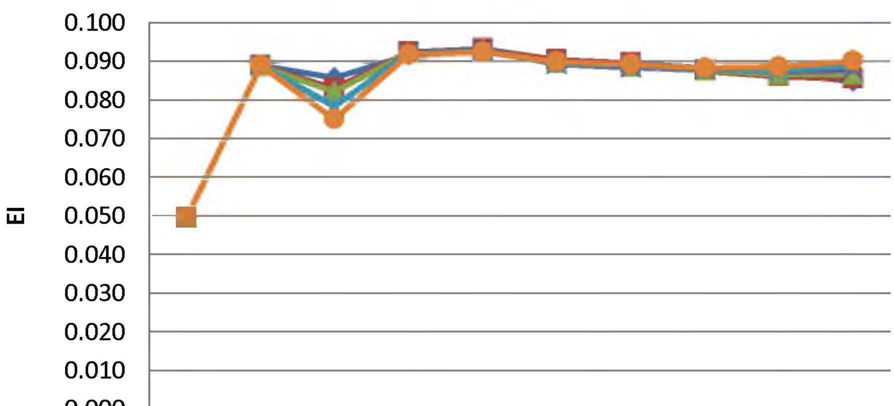
	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
BASE	0.13	0.10	0.10	0.10	0.13	0.17	0.19	0.21	0.22	0.24
RPS10	0.13	0.10	0.10	0.10	0.13	0.17	0.19	0.20	0.22	0.23
RPS20	0.13	0.10	0.09	0.10	0.13	0.16	0.19	0.20	0.22	0.23
RPS30	0.13	0.10	0.09	0.10	0.13	0.16	0.19	0.20	0.21	0.22
RPS40	0.13	0.10	0.09	0.10	0.13	0.16	0.18	0.19	0.21	0.22
RPS50	0.13	0.10	0.09	0.10	0.13	0.16	0.18	0.19	0.21	0.22

Fig. 14. Vulnerability under Carbon Tax Scenario



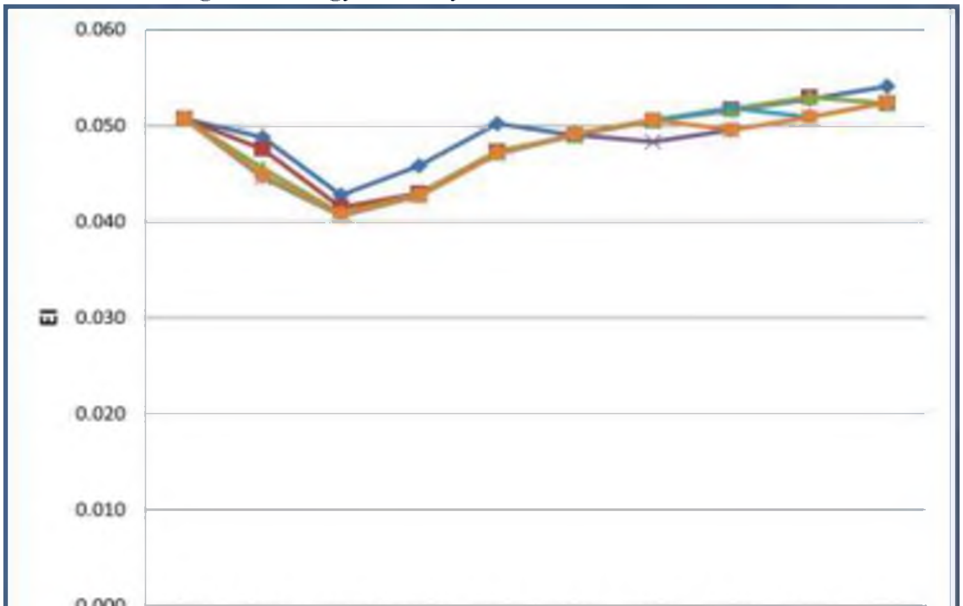
	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
BASE	0.12	0.11	0.09	0.10	0.15	0.18	0.20	0.21	0.23	0.25
CT10	0.12	0.10	0.08	0.09	0.14	0.17	0.19	0.21	0.22	0.27
CT15	0.12	0.10	0.08	0.09	0.14	0.17	0.19	0.21	0.25	0.27
CT20	0.12	0.10	0.08	0.09	0.14	0.17	0.19	0.23	0.25	0.26
CT25	0.12	0.10	0.08	0.09	0.14	0.18	0.22	0.23	0.25	0.26
CT30	0.12	0.10	0.08	0.11	0.16	0.19	0.22	0.23	0.25	0.26

Fig. 15. Energy Intensity under Renewable Portfolio Supply Scenario



	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
BASE	0.049	0.089	0.086	0.092	0.093	0.090	0.090	0.088	0.087	0.085
RPS10	0.049	0.089	0.083	0.092	0.093	0.090	0.090	0.087	0.086	0.085
RPS20	0.049	0.089	0.082	0.092	0.093	0.090	0.089	0.088	0.087	0.087
RPS30	0.049	0.089	0.078	0.092	0.093	0.089	0.088	0.088	0.087	0.088
RPS40	0.049	0.089	0.078	0.092	0.093	0.089	0.089	0.088	0.088	0.089
RPS50	0.049	0.089	0.075	0.092	0.092	0.090	0.089	0.088	0.088	0.090

Fig. 16. Energy Intensity under Carbon Tax Scenario



	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
BASE	0.051	0.049	0.043	0.046	0.050	0.049	0.051	0.052	0.053	0.054
CT10	0.051	0.048	0.041	0.043	0.047	0.049	0.050	0.052	0.053	0.052
CT15	0.051	0.046	0.041	0.043	0.047	0.049	0.051	0.052	0.053	0.052
CT20	0.051	0.045	0.041	0.043	0.047	0.049	0.048	0.050	0.051	0.052
CT25	0.051	0.045	0.041	0.043	0.047	0.049	0.051	0.052	0.051	0.052
CT30	0.051	0.045	0.041	0.043	0.047	0.049	0.051	0.050	0.051	0.052

Fig. 17. Green House Gas Emission under Renewable Portfolio Supply Scenario

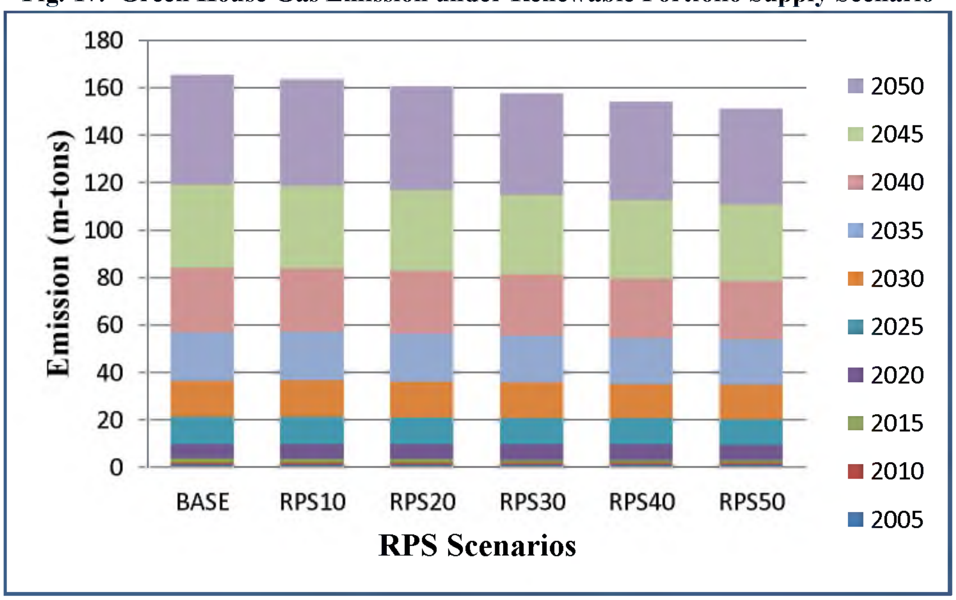
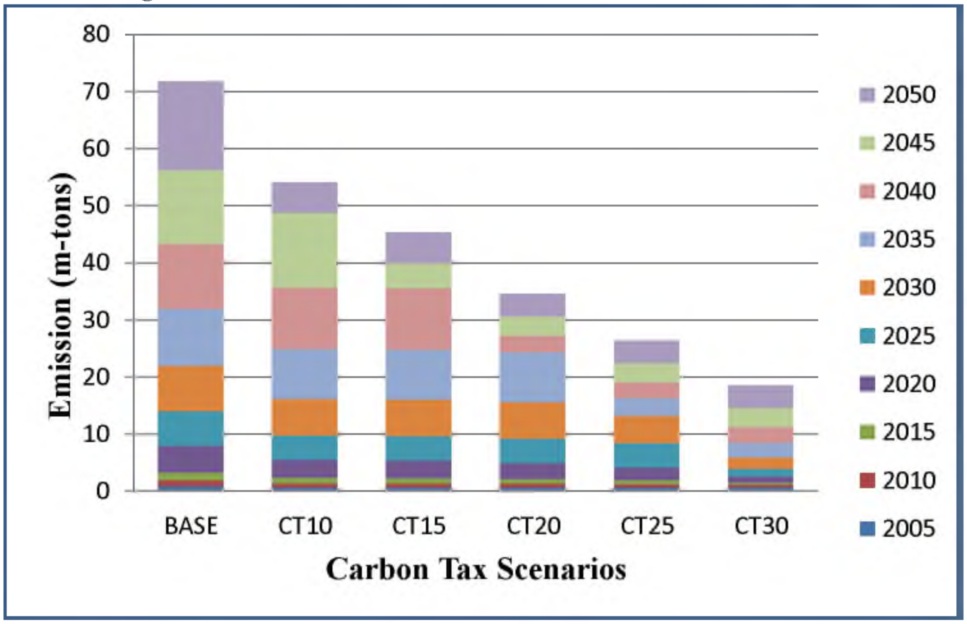


Fig. 18. Green House Gas Emission under Carbon Tax Scenario



6. CONCLUSIONS

This paper investigates the effects of renewable supply portfolio and carbon tax policies on diversification of energy resources, technology mix in energy supply side and demand side; energy efficiency and energy conservation; and energy security during the planning horizon 2005-2050. A MARKAL-based model for an integrated energy system of Pakistan was developed for this cause.

Renewable Portfolio Supply (RPS) is an important policy option to improve energy security. Renewable energy promotion is used to reduce emission, promote local energy sources and improve energy security through reducing energy dependency and diversification of energy sources. As more renewable energy resources are exploited and entered into the energy system, the energy import dependency decreases by 3 percent in RPS50 scenario, which is a considerable reduction in energy import dependency. Diversification of primary energy sources measured through DoPED and Shannon-Wiener Index (SWI) demonstrate 5 percent increase in diversification of the primary energy supply mix of the future energy system. Declining vulnerability and intensities in RPS Scenarios reflect enhanced energy security in long run. All the energy security indicators reflect better position under renewable portfolio supply scenarios; therefore Renewable Portfolio Supply (RPS) is a suitable policy option for energy security improvement in the long term in case of Pakistan.

Carbon tax is an indirect policy option for energy security enhancement through emission reduction. Imposing tax on carbon emission will alter the primary energy supply mix, more efficient fuel and technologies will be substituted for less efficient fuel and technologies. This will reduce the primary energy demand and lead to improved energy security. Under carbon tax, import dependency has reflected an increasing trend, while diversification of energy resources, vulnerability and energy intensity show better energy security up to 2035. Therefore Carbon Tax Policy may be a suitable policy option for energy security improvement in the long term.

Under Renewable Portfolio Supply (RPS) and Carbon Tax scenarios, Green House Gases (GHG) emissions are reduced by 9 percent, which is a significant reduction. This reduction in GHG emission is a sign of environmental security. So these two policy options not only enhance energy security, but also ensure environmental security.

Appendices

APPENDIX-A

End-use Demand Technologies

Sector		**End-use Demand Technologies**
Agriculture		Tractors and Electric Motors
Commercial		AC, Lighting, Refrigerators, Thermal Use and Other Electric Appliances
Industrial		Cement, chemical, electricity, equipment, food, paper, steel, sugar, textile, others.
Residential		Air-conditioning, cooking, fan, iron, lighting, refrigerator, TV and other electric appliances.
Transport	Air Passenger	Air plane
	Air Freight	Air Plane
	Water Freight	Ship
	Rail Passenger	Locomotive rail
	Rail Freight	Locomotive rail
	Road Passenger	Car, bus, van, pickup, taxi, three-wheelers, two-wheelers
	Road Freight	Trucks, Tankers, Pickups

APPENDIX-B

Conversion Technologies

Technology	**Fuel Type**
Power Generation	
Hydro	
a) Hydro	Reservoir
b) Hydro	Canal
Fossil Fuels	
a) Fluidised bed combustion(FBC)	Coal
b) Gas Turbine	Gas and HSD
c) Combine Cycle	Gas and HSD
d) Gas Turbine	Gas
e) Steam	Dual Fuel Combustion (Gas + FO)
f) Oil Fired	Fuel Oil
g) Gas Turbine Combine Cycle	Gas and FO fired Gas and HSD oil Fired
Nuclear	
a) Nuclear Power Plant	Uranium
Renewable	
Solar Photovoltaic, Solar Thermal, Wind Turbine, Mini Hydro	
Process Technologies	
a) Oil refinery	Crude Oil
b) Gas Processing Plant	Natural Gas

APPENDIX-C

Model Formulation

Objective Function of the Integrated Energy System Cost Model

The objective function is the sum over all of the discounted present value of the stream of annual costs incurred in each year of the horizon (no reference for this?). Therefore:

$$NPV = \sum_{r=1}^{R} \sum_{t=1}^{t=NPER} (1+d)^{NYRS.(1-t)} . ANNCOST(r,t).(1+(1+d)^{-1} + (1+d)^{-2} + \cdots + (1+d)^{1-NYRS} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

where, *NPV* is the net present value of the total cost for all regions, *ANNCOST(r, t)* is the annual cost in region *r* for period *t*, *d* is the general discount rate, *NPER* is the number of periods in the planning horizon, *NYRS* is the number of years in each period *t*, *R* is the number or regions.

In order to minimise total discounted cost, the MARKAL model must satisfy a number of constraints. These constraints show the physical and logical relationships to describe the associated energy system.

(a) Satisfaction of Energy Service Demands

For each time period *t*, region *r*, demand *d*, the total activity of end-use energy technologies must be at least equal to the specified demand. Hence:

$$\sum_{k}^{all\ d} CAP(r,t,k) \geq D(r,t,d) \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

where *CAP*(*r, t, k*) is the installed capacity of technology *k*, in period *t*, in region *r*, *D*(*r, t, d*) is the energy demand for end-use *d* in region *r*, in period *t*.

(b) Use of Capacity

In each time period, the model may use some or all of the installed capacity according to the technology availability factor (AF) i.e. the model may utilise *less* than the available capacity during certain time-slices, or even throughout one whole period. Therefore, the activity of the technology may not exceed its available capacity.

$$ACT(r,t,k,s) \leq AF(r,t,k,s)\ CAP(r,t,k) \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

where *ACT*(*r, t, k, s*) is the activity level of energy technology *k*, in period *t*, in region *r*, for time slice *s*, *AF*(*r, t, k, s*) is the availability parameters.

(c) Demand-Supply of Energy Balance

For each commodity *c,* time period *t*, region *r*, this constraint requires that the disposition of each commodity may not exceed its supply.

$$\sum_k Output(r,t,k,c)\ ACT(r,t,k,s) + \sum_l MINING(r,t,c,l) + \sum_l FR(s) IMP(r,t,c,l) \geq \sum Input(r,t,k,c) ACT(r,t,k,c,s) + \sum_l FR(s)\ EXP(r,t,c,l) \quad \ldots \quad (4)$$

where *Output*(*r*, *t*, *k*, *c*) is the amount of energy commodity c, produced per unit of technology *k* in region *r* in period *t*, *MINING*(*r*, *t*, *c*, *l*) is the quantity of energy commodity *c* extracted in region *r* at price level *l* in period *t*, *FR*(*s*) is the fraction of the year covered by time-slice *s*, *IMPORT*(*r*, *t*, *c*, *l*) is the quantity of energy commodity *c*, price level *l*, exogenously imported or exported by region *r* in period *t*, *Input*(*r*, *t*, *k*, *c*) is the amount of energy commodity *c* required to operate one unit of technology *k*, in region *r* and period *t*, *EXPORT*(*r*, *t*, *c*, *l*) is the quantity of energy commodity *c*, price level *l*, exogenously imported or exported by region *r* in period *t*.

REFERENCES

Alhajji, A. F. (2007) What Is Energy Security? Definitions and Concepts. *Middle East Economic Survey* 50:45.

Alhajji, A. F. and James L. Williams (2003) Measures of Petroleum Dependence and Vulnerability in OECD Countries. *Middle East Economic Survey* 46:16.

Anwar, J. (2010) Analysis of Energy Security using Partial Equilibrium Model: A Case of Pakistan. *The Pakistan Development Review* 49:4, 925–940.

APEC Energy Demand and Supply Outlook (2006) Projections to 2030. *Economy Review*.

Asia Pacific Energy Research Centre (2003) *Energy Security Initiative*.

Asia Pacific Energy Research Centre (APERC) (2007) *A Quest for Energy Security in the 21st Century*. Japan: Institute of Energy Economics, Japan.

Asif, M. (2009) Sustainable Energy Options for Pakistan, *Renewable and Sustainable Energy Reviews* 13, 903–909.

Bahgat, G. G. (2005) EU Seeks Energy Security in Stronger Suppliers Ties. *Oil and Gas Journal*, Oct 10, 2005.

Bertel, E. (2005) Nuclear Energy and the Security of Energy Supply. *Facts and Opinions, NEA News* 2005—No. 23.2.

Bielecki, J. (2002) Energy Security: Is the Wolf at the Door? *The Quarterly Review of Economics and Finance* 42:2, 235–250.

Blyth and Leferve (2004) Energy Security and Climate Change Policy Interactions: An Assessment Framework. (IEA Information Paper).

Bohi, D. R. and M. A. Tom (1996) *The Economics of Energy Security*. Kluwer Academic Publishers: Boston/Dordrecht/London.

Bohi, Douglas R. (1989) *Energy Price Shocks and Macroeconomic Performance*. Resources for the Future Washington (DC).

Bohi, Douglas R. and W. D. Montgomery (1982) *Oil Prices, Energy Security and Import Policy*. Resources for the Future Washington (DC).

Christoph, W. Fre (2004) The Kyoto Protocol—A Victim of Supply Security? Or: If Maslow were in Energy Politics. *Energy Policy* 32, 1253–1256.

Clingendael Institute/Clingendael International Energy Programme (CIEP) (2004) EU Energy Supply Security and Geopolitics (Tren/C1-06-2002) CIEP Study. The Hague, Netherlands.

Costantini, V., F. Gracceva, A. Markandya, and G. Vicini (2007) Security of Energy Supply: Comparing Scenarios from a European Perspective. *Energy Policy* 35:1, 210–226.

European Commission (2001) Green Paper: Towards a European Strategy for the Security of Energy Supply.

Fishbone, L. G., G. Giesen, H. A. Hymmen, M. Stocks, H. Vos. D. Wilde, D., R. Zoelcher, C. Balzer, and H. Abilock (1983) Users Guide for MARKAL: A Multi-Period, Linear Programming Model for Energy Systems Analysis. BNL Upton, NY, KFA, Julich, Germany, BNL 51701.

Gnansounou, E. and J. Dong (2004) Opportunity for Inter-regional Integration of Electricity Markets: The Case of Shandong and Shanghai in East China. *Energy Policy* 32:15, 1737–1751.

Grubb, M., L. Butler, and P. Twomey (2006) Diversity and Security in UK Electricity Generation: The Influence of Low-carbon Objectives. *Energy Policy* 34:18, 4050–4062.

Helm, D. (2006) Energy Policy: Security of Supply, Sustainability and Competition. *Energy Policy* 30:3, 173–184.

Hillard, G. Huntington and P. A. Brown Stephen (2004) Energy Security and Global Climate Change Mitigation. *Energy Policy* 32, 715–718.

Hogan, Lindsay, Lindsay Fairhead, and Andrew Gurney (2005) Energy Security in APEC: Assessing the Costs of Energy Supply Disruptions and the Impacts of Alternative Energy Security Strategies. (ABARE Research Report 05.2).

IEA (2004) *World Energy Outlook 2004*. Paris: International Energy Agency.

IEA (2007a) *Energy Security and Climate Change; Assessing Interactions*. Paris: International Energy Agency.

IEA (2007b) *Contribution of Renewable to Energy Security*. Paris: International Energy Agency.

IEA (2007c) *World Energy Outlook 2007– China and India Insights*. Paris: International Energy Agency.

Kruyt, B., *et al.* (2009) Indicators for Energy Security. *Energy Policy*.

LaCasse, C. and A. Plourde (1995) On the Renewal of Concern for the Security of Oil Supply. *The Energy Journal* 16:2, 1–24.

Li, Xianguo (2005) Diversification and Localisation of Energy Systems for Sustainable Development and Energy Security. *Energy Policy* 33, 2237–2243.

Loulou, R. and A. Kanudia (1998) The Kyoto Protocol, Inter-Provincial Cooperation, and Energy Trading: A Systems Analysis with Integrated MARKAL Models, GERAD Discussion PaperG-98-42, GERAD and McGill University, Montréal, Canada.

Loulou, R., G. Goldstein, and K. Noble (2004) Energy Technology Systems Analysis Programme: Documentation for the MARKAL Family of Models.

Lucia, Pantelimon (1999) Technological Development and Strategies for Achieving Energy Security and Constraints. *Applied Energy* 64, 307–310.

Mamdouh, G. Salameh (2003) The New Frontiers for the United States Energy Security in the 21st Century. *Applied Energy* 76, 135–144.

Maw, U. K. M. (2005) Current Energy Situation and MARKAL Activities in Myanmar, Annex IX Technical Conference, ETSAP Taipei, Taiwan, 4–7 April 2005.

Mirza, U. K., M. Mercedes Maroto-Valer, and Nasir Ahmad (2003) Status and Outlook of Solar Energy Use in Pakistan. *Renewable and Sustainable Energy Reviews* 7, 501–514.

Mirza, U. K., M. Nasir Ahmad, and Tariq Majeed (2007) An Overview of Biomass Energy Utilisation in Pakistan. *Renewable and Sustainable Energy Reviews* 7, 501–514.

Mirza, U. K., M. Nasir Ahmad, Tariq Majeed, and Khanji Harijan (2007a) An Hydropower use in Pakistan: Past, Present and Future. *Renewable and Sustainable Energy Reviews* 12, 1641–1651.

Mirza, U. K., M. Nasir Ahmad, Tariq Majeed, and Khanji Harijan (2007b) Wind Energy Development in Pakistan. *Renewable and Sustainable Energy Reviews* 11, 2179–2190.

Muneer, T. and M. Asif (2005) Prospects for Secure and Sustainable Electricity Supply for Pakistan. *Renewable and Sustainable Energy Reviews* 20, 1–19.

Neff, L. T. (1997) Improving Energy Security in Pacific Asia: Diversification and Risk Reduction for Fossil and Nuclear Fuels. Center for International Studies. Massachusetts Institute of Technology.

Owen, Anthony D. (2004) Oil Supply Insecurity: Control versus Damage Costs. *Energy Policy* 32, 1879–1882.

Pakistan, Government of (2006-07) *Pakistan Economic Survey 2006-07*. Islamabad: Ministry of Finance, Government of Pakistan.

Pakistan, Government of (Various Years) *Pakistan Energy Yearbook 1995 to 2005*. Islamabad: Hydrocarbon Development Institute of Pakistan.

Saghir, Jamal (2006) World Bank Perspective on Global Energy Security, G8 Energy Ministerial Meeting, March 16, 2006 Moscow.

Sahir, Mukhtar H. and Arshad H. Qureshi (2007) Specific Concerns of Pakistan in the Context of Energy Security Issues and Geopolitics of the Region. *Energy Policy* 35 2031–2037.

Siddiqi, Toufiq A. (1995) India-Pakistan Cooperation on Energy and Environment to Enhance Security. *Asian Survey* 35, 280–290.

Tempest, P. (2004) Energy Security in an Insecure World. IAEE News Letter 1st Quarter 2004, pp. 19-20.

Verma, Shiv Kumar (2007) Energy Geopolitics and Iran–Pakistan–India Gas Pipeline. *Energy Policy* 35, 3280–3301.

World Economic Outlook Database (October 2008) International Monetary Fund.

Wright, Philip (2005) Liberalisation and the Security of Gas Supply in the UK. *Energy Policy* 33, 2272–2290.