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Carbon pricing and energy efficiency improvement – why to miss the interaction for developing economies? An illustrative CGE based application to the Pakistan case

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HIGHLIGHTS

- Carbon tax & energy efficiency progress possibly cause GDP loss & rebound effects.
- The interaction of the two policy measures can reduce these unintended effects.
- The impact of CT for Pakistan found fairly moderate with high emissions reduction.
- Coordinated implementation approach further lower GDP loss with less energy demand.
- CT showed potential of reducing emissions of local pollutants even at a higher rate.

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ABSTRACT

Carbon/energy taxes and energy efficiency improvement are studied well in the recent years for their potential adverse impacts on economy, especially for lost production and international competitiveness, and rebound effects. However, little attention has been paid to investigate them jointly, which can not only prevent fall of energy services cost and thereby rebound effect but reduce the associated macroeconomic costs. This study thus employs a 20 sector CGE model to explore separately the impacts of carbon tax and its coordinated implementation with energy efficiency improvement on the Pakistan economy. The country underwent enormous pressure of energy security issues as well as climate change fallouts in the last couple of years and can be regarded as a suitable candidate for energy/environmental conservation policies to be considered at a broader context with more concrete efforts. The simulation results show that the impact of carbon tax on GDP is negative but resulting reductions in pollutant emissions are relatively high. Moreover, the GDP is expected to grow comparatively positive when analyzed with improvements in energy efficiency, with even higher decline in energy consumption demand and so emissions. This simultaneous economic and environmental improvement would thus have positive implications regarding sustainable development of the country.

1. Introduction

The potential impacts of greenhouse gases reduction at both national and international level, generally under the most elegant and logical mechanism of computable general equilibrium (CGE) models, are well studied in the recent decades. The real need for use of the CGE modeling approach for such investigations primarily stems from its capabilities of capturing interlinkages between economic development, environmental quality, and social progress, as well as the feedback effects for different policy initiatives (Naqvi, 1998; Yang, 2001).

In the existing climate literature, both market-oriented instruments (such as taxes, tax exemptions, and subsidies etc.) and other non-market regulatory measures (e.g. mandated targets) are found to be analyzed (see for instance O'Ryan et al., 2005; Wissema and Dellink, 2007; Loisel, 2009; Xu and Masui, 2009; Lu et al., 2010; Dai et al., 2011). The macroeconomic costs especially in terms of GDP loss of these policy implementations are mostly observed positive (IPCC, 2007). Exceptions include, though viewed difficult to sustain, revenue neutrality approach where climate tax regime coincides with appropriate fiscal adjustments by lowering other distortionary taxes (such as taxes on labor and capital) in the system, thus generating double

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dividend effect of improving both environment and economy simultaneously (Baranzini et al., 2000).

On the contrary, the energy efficiency improvement is considered a powerful and cost-effective way to promote sustainable development through a collective realization of economic growth, cleaner environment, and social development (WB, 2009). The recent international studies also portray a very bright purview of energy efficiency growth in climate emissions mitigation. IEA, for example, estimates that in achieving the 450 scenario (where policies are assumed to be introduced in a way so that atmospheric GHGs concentration stabilizes at 450 parts per million—ppm of CO_2 equivalent), when compared with the new policy scenario, 76% in 2020 and 43% in 2035 of the world energy-related CO_2 emissions reduction will take place solely due to energy efficiency growth (IEA, 2010a). In addition, in developing countries where energy use per unit of GDP is already very high compared to their developed counterpart (IEA, 2010b), the prospects of energy efficiency improvement even at a higher rate can never be ruled out.

The energy efficiency growth though remained on international forefronts since quite a long (including the more recent developments such as Eco-efficiency and Factor 10), the associated possibility of rebound or take-back effects is generally not given the due consideration (Grepperud and Rasmussen, 2004). The rebound effect formally known as Khazzoom–Brookes Postulate (Saunders, 1992) defines that energy efficiency improvement may result in increased demand for the services energy helps to provide and therefore erode partially or wholly the likely energy saving gains. The demand effects stem from increased supply of energy services which consequently decreases the effective energy prices (for more recent analyses on rebound effect, see e.g. Grepperud and Rasmussen, 2004; Hanley et al., 2006, 2009; Allan et al., 2007; Anson and Turner, 2009; Turner, 2009 etc.).

The rebound effect though has a sound theoretical basis, no consensus exists on its magnitude. It varies widely ranging from near zero to well above 100%—the phenomenon, typically occurs in selected instances in the medium to long term, is commonly cited as 'backfire' in the literature and used to exhibit increase in overall energy consumption. The estimates of direct rebound effect (energy savings forgone solely due to increased welfare) fall generally below 30%, unlike indirect effects (arise from income gains which subsequently stimulate consumption and energy demand) and economy-wide rebound effects which are found to vary quite substantially. For example, the economy-wide rebound effect estimates reported by the CGE studies over time range from an insignificant 15% to an alarming 350%. The inconclusive results produced by these studies thus further dispels the notion that energy efficiency by itself can help halt global GHGs emission accumulation in the atmosphere (Greening et al., 2000; Saunders, 2000; Dimitropoulos, 2007).

Since governments tend to announce policy packages, simultaneous analysis of different climate policy instruments thus becomes even more important. The energy efficiency improvement which instigate rebound effects and therefore offsets the potential energy savings can be complemented with appropriate carbon/energy pricing either through taxation or emission trading scheme so that energy services costs do not fall. This will not only lesson the rebound effects but also reduce the negativities associated with carbon/energy taxes especially in terms of lost production and international competitiveness (UKERC, 2007; Turner and Hanley, 2011). Hanley et al. (2009) quotes Birol and Keppler (2000) who also viewed technology and relative price related policies as complementary, and go on further to assert that combination of energy policies involving taxes with revenue recycling to reduce other distortionary taxes and efficiency stimuli can potentially generate a genuine double dividend of bolstering economy and environment simultaneously. Similar arguments are put forward by Hanley et al. (2006) where it is emphasized that policies designed to stimulate energy efficiency cannot, in and of themselves, be relied upon for environmental improvements; rather to ensure such improvements, energy efficiency improvements may have to be combined with other polices meant to discourage greater energy consumption.

Existing CGE studies use climate policy instruments especially energy efficiency and emission taxation separately to analyze for their potential effects. No attention has been paid particularly for developing countries where much room is available to exploit the energy efficiency improvements to investigate them jointly (a relatively analogous investigation is Brannlund et al. (2007), where an econometric model is used to examine the impacts of exogenous technological progress in terms of an increase in energy efficiency on Swedish households consumption choice and thereby emissions of pollutants including CO_2; necessary changes in CO_2 tax are then proposed to neutralize the rebound effect and keep CO_2 emissions at their initial level). The present study, therefore, attempts in the direction and try to comprehend the joint effects of energy efficiency and carbon tax policies for Pakistan.

This analysis is also of special interest in that there has been a lack of any climate discussion in the recent years under CGE framework for Pakistan. The two pioneer projects could be spotted in the field by the authors include Shah and Larsen (1992) and Naqvi (1998). The former is a World Bank study where a dynamic model is used to analyze the impact of a US$10 carbon tax on manufacturing industries as a whole and separately for apparel and leather products industries of Pakistan for the period 1966–1984. Distributional implications are also calculated by using 1984–1985 Household Income and Expenditure Survey data. The later study, however, used a static model built around 1983–1984 social accounting matrix for short-run policy simulations and analyzed mainly the price dynamics related to energy sector, and tried to capture the interlinkages between economy, energy and equity for the country. In this background, the present study therefore intends to examine implementation of climate policies for their potential economic and environmental effects and thereby compliment and improve the current literature by including recent assessments for a big developing country, Pakistan.

The rest of the article is categorized as follows. The next, Section 2 gives a brief description of the current energy/environment situation of the country. Section 3 provides introduction and theoretical setting of the dynamic model build for this study. Section 4 explains sources, structure, and construction of the database and the parameters exogenously defined in the model. The scenario formulation and simulation results are discussed in Section 5, whereas Section 6 is devoted for sensitivity analysis to check the robustness of the results. Finally, Section 7 presents summary and major conclusions of the analysis. The mathematical formulation (equations) of the model is presented at the end in Appendix A.

2. Energy/environment situation of Pakistan

Pakistan is basically an energy deficient country. The per capita TPES and electricity consumption for the country, in the year 2010, were estimated at mere 0.49 toe and 457 kWh; against the average TPES of the world, OECD and Asian countries (excluding China) at 1.86, 4.39, and 0.68 toe and average electricity consumption at 2892, 8315, and 806 kWh per capita, respectively (IEA, 2010a). Overall electrification rate was observed at 67%, much below than world average electrification rate of 81%, with a total of

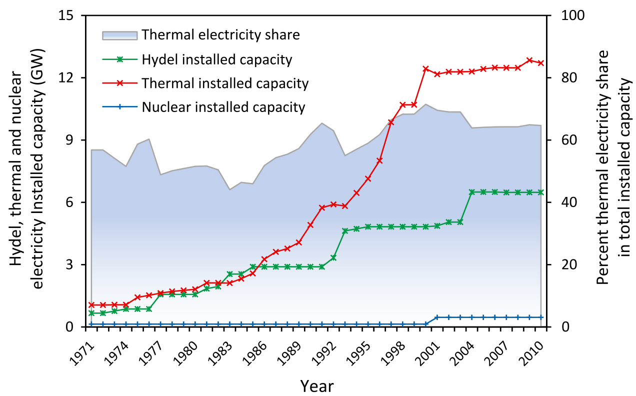

Fig. 1. Installed hydel, thermal and nuclear electricity capacity (left scale), and thermal share in total electricity installed capacity (right scale) of the country during 1971 to 2010. *Data source*: (SBP, 2010a).

approximately 56 million people having no access at all to the electricity services (ADB, 2013).

Total primary energy supply (TPES) of the country (comprising commercial energy plus traditional fuels such as fuel wood, crop residues, and animal wastes) was 17 million toe in 1971 which increased, at an average annual growth rate of 10.20%, to 84.6 million toe, with 63.09 million toe of commercial primary energy supply, in 2010 (HDIP, 2010; IEA, 2012b).

For final energy consumption mix of the country, it was largely oil dominated in the late 1990s, which in the following years gradually shifted towards indigenous sources such as coal and gas mainly due to the highly volatile international oil prices. The oil consumption grew, for example, at an average annual rate of −0.02% during 1997 to 2010 compared to the noticeably higher growth rates of 12.01% and 15.31% per annum for gas and coal, respectively. This consequently led the oil share to drop from a high 47.97% to 27.93% and increase in gas and coal shares from 29.37% and 6.33% to 43.91% and 11.05%, respectively, during the period. Conversely, for electricity consumption, it increased at a relatively modest annual average rate of 5.63% and without any significant change in its share in total final energy consumption mix which remained between 14% to 16% throughout the period. The LPG consumption share in 1997 was a meager 0.89%, which grew to 1.49% in 2010 (HDIP, 2000, 2005, 2010; FD, 2009).

Historical energy data reveals that the country's dependence on imported fuel increased in the recent decades due to the growing demand for household sector/other production industries as well as the widening gap between domestic consumption and supply. The net energy imports (percent of energy use) observed to be 23.99% in 2010 against 15.76% in 1971. Major import contributions, in the year 2010, appeared from crude oil (69.3% of the total crude) and refined petroleum products (54.9% of the total domestic production from both domestically produced and imported crude) (HDIP, 2010; WB, 2013). One of the important factors that contributed significantly in continuous surge of fuel demand in the past included thermal electricity generation (electricity generation capacity of the country over time is shown in Fig. 1). Despite abundant hydro potential of the country – 46 GW out of which only 14% is harnessed so far (PC, 2007) – thermal power generation increased at an average rate of 24.32% per annum compared to 14.93% for hydel electricity generation during 1971 to 2010; thus an estimated 58 percentage point increase was observed in thermal to hydel electricity generation ratio over the period. Total electricity generation in 2010 was estimated at 39.34 TWh, with hydel, thermal, and nuclear shares of 35.99, 60.16, and 3.85%, respectively (SBP, 2010a).

Regarding environmental issues, though level of some pollutants such as sulpher dioxide (SO_2), oxides of nitrogen (NO_x), ozone (O_3) etc. in the ambient air is believed within safe limits in Pakistan (FD, 2012), other pollutant emissions originating from fuel combustion especially GHGs are increasing rapidly. For example, CO_2 emissions, according to IEA estimates, reached to 134.6 million tons in 2010 from just over 16 million tons in 1971 (using the relevant time series data, contributions of energy intensity, CO_2 intensity, economic growth, and population expansion in CO_2 emissions over the period 1971–2010 are decomposed by the authors and presented in Table 1). High growth of CO_2 emissions in the recent years was recorded at 11.5%, 8.1%, and 9.4% for 2004, 2006, and 2007, respectively. The average annual CO_2 emission growth rates were observed at 4.9% for 1970s, 8.8% for 1980s, 5.8% for 1990s, and 3.5% for 2000s. For sectoral CO_2 emissions, manufacturing industries and construction, electricity and heat production, and road transport were the major contributing sectors in 2010, with shares of 31.5, 29.79, and 23.48%, respectively; while household emissions constituted only 9.7% of the total CO_2 emissions for the year (IEA, 2012b).

Table 1
Decomposition of carbon dioxide (CO_2) emissions over 1971–2010 (million tons)[a].

Energy intensity of GDP effect	CO_2 intensity of TPES effect	Economic growth effect	Population expansion effect	Total change in CO_2 emissions
−17.22	+29.60	+50.03	+61.39	+123.80

[a] The signs reflect increase (+) or decrease (−) in CO_2 emissions.
Source: Authors' calculations.

As per 2010 estimates, Pakistan's total CO_2 emissions, including emissions from fossil fuel burning, gas flaring and cement production, after witnessing an annual average growth rate of 5.9% since 1972, stood at 163.27 million tons. According to the available data for 2009, Pakistan was ranked 31st for its total CO_2 emissions and 153rd for per capita CO_2 emissions in the world (CDIAC, 2013).

Although Pakistan's total GHG emissions are low compared to international standards, the government is planning to target specifically energy and agriculture sectors for their mitigation efforts. Introduction of carbon tax on the use of fossil fuels is laid out as an important policy measure to reduce energy sector's GHG emissions, which is the single largest source with nearly 51% of the total emissions in the country (MoCC, 2012). Besides, owing to the facts that: (i) the country was listed in the top 10 most effected countries since 1991 to 2010 in the long-term climate risk index (Harmeling, 2012) and under extreme risk category for the most vulnerable countries over the next 30 years in the climate change vulnerability index 2011 (Maplecroft, 2011), and (ii) as IPCC projected that without effective policy actions by the governments, GHG emissions from fossil fuel combustion will rise by over 50% by 2030 (IPCC, 2007), Pakistan's contribution in GHG emissions reduction is thus highly sought.

3. Theoretical specification of the model

A recursive dynamic general equilibrium model, named TECGE (acronym for tax-efficiency CGE model), is developed for this study. The model consists of prices, production, trade, investment, income & expenditure, equilibrium, and pollution blocks. Sectoral aggregation scheme of the model considers 4 energy and 16 non-energy sectors, namely: (1) agriculture, (2) crude oil and natural gas, (3) other minerals, (4) Food, beverages and tobacco, (5) textile and wearing apparel, (6) paper, wood and furniture, (7) chemicals and chemical products, (8) basic metal products, (9) fabricated metal products, (10) other non-metallic mineral products, (11)

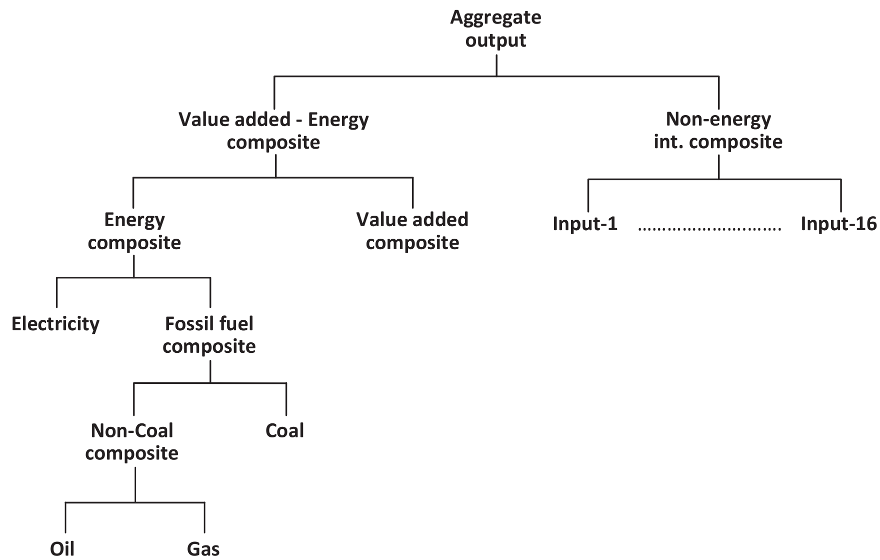

Fig. 2. KLEM nesting production framework of the 20 sector/product TECGE model for Pakistan.

electrical equipments, (12) other non-electrical machinery, (13) other manufacturing products, (14) coal products, (15) oil products, (16) gas supply, (17) electricity, (18) construction, (19) transport services, and (20) other services. Primary inputs or factor of production include capital and labor. A single representative household is considered along with government and rest of the world institutional units.

3.1. Production structure

Production structure of a CGE model defines optimal input selection path either for profit maximization or cost minimization under certain constraints such as technical substitutability for decision making entities to produce domestic output. The inputs include intermediate material inputs, energy, and primary inputs. In TECGE model, a multilayer nesting structure is adopted (see Fig. 2) to allow maximum substitution possibilities. Total gross output is assumed a function of non-energy intermediate inputs, energy, labor, and capital, i.e. KLEM (capital–labor–energy–materials) approach is adopted which is most commonly used in the energy and environment related CGE studies. Non-joint production and single technological nesting structure is assumed for all the production sectors.

At the highest level of production, fixed proportion or Leontief function is used between non-energy intermediate and capital–labor–energy composites. Similar formulation of zero elasticity is also assumed between non-energy intermediate inputs. However, in all the subsequent nesting levels, constant elasticity of substitution (CES) function is used to describe the substitution relationships, for which the primal and dual functions can be written in the following generalized forms:

$$Z_i = \beta_i^z[\alpha_i^z (U_i e_i^u)^{-\rho_i^z} + (1-\alpha_i^z)(V_i e_i^v)^{-\rho_i^z}]^{-1/\rho_i^z} \tag{1}$$

$$PZ_i = \frac{1}{\beta_i^z}\left[\alpha_i^{z\sigma_i^z}\left(\frac{PU_i}{e_i^u}\right)^{(1-\sigma_i^z)} + (1-\alpha_i^z)^{\sigma_i^z}\left(\frac{PV_i}{e_i^v}\right)^{(1-\sigma_i^z)}\right]^{1/(1-\sigma_i^z)} \tag{2}$$

where Z_i is the aggregate output from the variables U_i and V_i, PZ_i is the unit cost derived from dual function, β_i^z is the scale parameter, α_i^z is the share parameter, e_i^x is the productivity growth parameter, σ_i^z is the substitution elasticity between U_i and V_i, and ρ_i^z is the CES function exponent parameter given by $\rho_i^z = (1-\sigma_i^z)/\sigma_i^z$. The PU_i and PV_i are the prices of U_i and V_i, respectively. Assuming a fully competitive market, the cost minimizing demand functions for U_i and V_i can be expressed in the following equations.

$$U_i = Z_i\left[(\beta_i^z e_i^u)^{-\rho_i^z}\alpha_i^z\left(\frac{PZ_i}{PU_i}\right)\right]^{\sigma_i^z} \tag{3}$$

$$V_i = Z_i\left[(\beta_i^z e_i^v)^{-\rho_i^z}(1-\alpha_i^z)\left(\frac{PZ_i}{PV_i}\right)\right]^{\sigma_i^z} \tag{4}$$

Since primal and dual functions embody the same information (Devaraian et al., 1994), either of the two can be used to devise the model equations. In this study, we have used primal formulation at the second level between capital–labor and energy composites, whereas dual formulation for all the following nests such as between capital and labor and between different energy inputs.

3.2. International trade

Pakistan is modeled as a price taker for its external sector. The total domestic demand is described by the Armington assumption (Armington, 1969) which differentiates domestic and foreign goods by origin and considers them as imperfect substitutes. The constant elasticity of substitution (CES) function is used to comprehend this relationship of imperfect substitutability between domestic and imported commodities. As for the total domestic production, it is allocated between domestic use and exports by using the constant elasticity of transformation (CET) function. The demands for domestic production for domestic use, imports, and exports are determined by the optimization of Armington CES and CET functions for minimization of domestic demand cost and maximization of domestic production revenues, respectively.

3.3. Income and expenditure behavior

The labor wages, capital rental and depreciation expenditures constitute total gross factor income of the model. Household income comes from payments for its factor endowments and net transfers from government and rest of the world institutional units. The disposable household income is obtained by deducting direct tax from the total income and divided further into saving and consumption expenditures by multiplying with the marginal private saving rate which is defined outside the model.

The government income is composed of property income, direct tax, indirect taxes less of production subsidies, import duties, and net transfers from rest of the world. The net government income which either can be consumed or saved is defined by subtracting government transfers to households from its total income. The marginal saving rate for the government is also decided exogenously in the model.

The linear expenditure system (LES) function is used to describe both household and government consumptions; which are subsequently converted into final goods consumption by using conversion matrices obtained from the benchmark year data.

3.4. Investment (GFCF & stock)

Total investment in the model is composed of gross fixed capital investment (GFCF) and stock investment. The stock investment of good i is set as a fixed share of total output of the corresponding sector. The expenditures on fixed capital investment are then maintained as a residual of the total investment function, which are further used to derive the supply of fixed investment goods based on fixed share matrix and investment goods prices.

3.5. Macroeconomic closures

The choice of setting exogenous or endogenous behavior of some of the variables commonly known as macroeconomic closure is mandatory for any model to be solved mathematically (Decaluwe and Martens, 1988). Three closure rules are followed in this study: (i) saving–investment closure, (ii) external closure, and (iii) general government closure. For saving–investment closure, the neoclassical approach is adopted and therefore real investment is determined based on the total available savings; for external closure, foreign saving or current account deficit is kept exogenous whereas exchange rate as endogenous; and for general government, there was budget deficit in the base year which is assumed exogenous while treating government consumption as endogenous and therefore decisive in attaining government revenue–expenditure balance.

3.6. Market equilibrium

The commodity or goods market equilibrium is achieved by equalizing the total domestic supply or Armington composite to the total domestic demand which consists of intermediate demand, final private and government demand, and investment.

For primary factors, the market is assumed perfectly competitive, thus allowing fully mobile factors across the production sectors. The average factor prices are flexible and can adjust freely to equilibrate the demand to its corresponding supply (Note: The sectoral wage rates are maintained as linear function of the corresponding average wage rate, whereas sectoral rental rates are determined based on the equilibrium of demand and supply of the sectoral capital stocks of the economy).

International trade and saving–investment balances are also satisfied in this model. In international trade balance, the exchange rate adjusts so that total inflows of the country equal total outflows, i.e. a zero current account balance is achieved. For saving–investment balance, the saving-driven neoclassical closure together with other equilibrium conditions adopted in this study satisfies the Walras law of market clearing for a closed system.

3.7. Pollutant emissions

This study considers emissions from only energy related use of fossil fuels, thus excluding other sources of emissions such as use of fertilizers, deforestation, and land use change. The emissions are calculated for each sector by multiplying fossil fuel consumption with their respective energy, emission, and fuel related use conversion factors. The pollutants considered in the model include carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and sulfur dioxide (SO_2). Single economy-wide representative energy prices are used in the model. The prices are calculated based on monetary energy accounts of the SAM and physical energy consumption data for the benchmark year of the study obtained from (HDIP, 2010). Since country specific emission factors especially for non-CO_2 pollutants were not available, default emission factors distinguished by five broad sectoral categories such as: (i) Residential/ Agriculture/ Forestry/ Fishing/Fishing farms, (ii) Manufacturing and construction, (iii) Energy industries, (iv) Road Transport, and (v) Commercial/Institutional, provided by IPCC for national greenhouse gas inventories (IPCC, 2006) are considered appropriate to be used for this analysis.

The emission tax rate and the additional per unit emission cost for fossil energy goods incurred due to carbon taxation are decided exogenously in the model. The additional per unit emission cost is calculated by multiplying the emission tax rate with the energy, emission, and fuel related use share coefficients. The new post-tax input price of fossil energy is then obtained as a function of its composite price and the additional per unit emission cost (for detailed discussion on pollution modeling, see O'Ryan et al., 2005; Hanley et al., 2006; Oladosu and Rose, 2007).

3.8. Recursive or between-period specification

Since a static model can only represent the economy for a particular time period and therefore cannot account for the effects that current changes such as investment decisions etc. can produce in later time periods in the economy, a recursive dynamic formulation is adopted in our study to incorporate inter-temporal behavior, albeit not affected by forward-looking expectations, and results from the simulations done for previous periods. The very conditions that govern dynamics in this model include between-period updation of factor (capital, labor) supply, factor productivity growth, energy efficiency growth, and saving behavior of economic agents.

The between-period labor supply growth is decided exogenously. However, the capital stock growth is endogenous and determined by the previous period capital stock, depreciation, and new investment supplied to the production sectors. It follows the relationship shown in Eq. (5).

$$KS_{j,t+1} = KS_{j,t}(1 - \tau_j^{dep}) + DI_{j,t} \tag{5}$$

where t represents yearly time periods, KS_j is the capital stock, τ_j^{dep} is the capital depreciation or wear and tear rate, and DI_j is the fixed investment supplied to the sector j. The DI_j is determined, following the mechanism adopted by Xu and Masui (2009), by using a logic function as given in Eq. (6).

$$DI_{j,t} = FI_{Total,\,t}\left[\frac{(R_{j,t:t=1})^{\vartheta}\,DI_{j,t=1}}{\sum_j\{(R_{j,t:t=1})^{\vartheta}\,DI_{j,t=1}\}}\right] \tag{6}$$

where FI_j is the fixed investment supplied by the sector j, R_j is the price of capital or rental rate in sector j, and ϑ is the investment propensity among sectors.

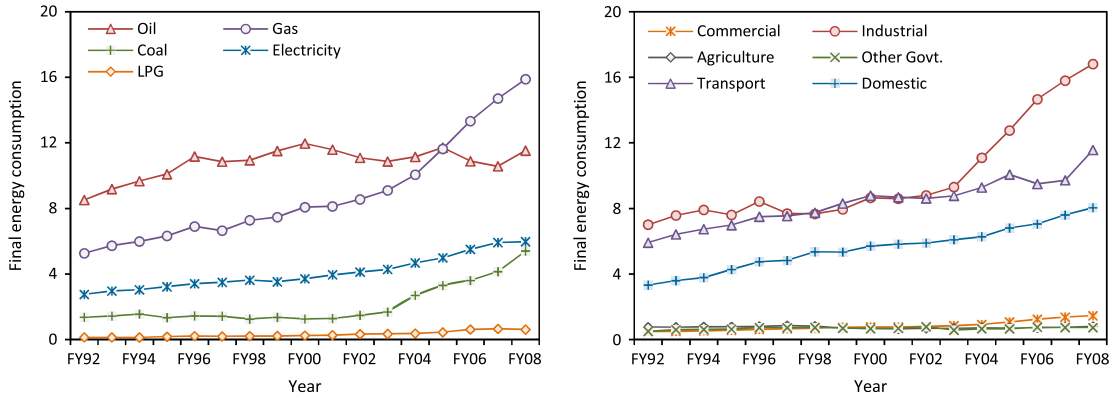

Fig. 3. Commercial energy consumption in million toe by source (left) and sector (right) during the financial years 1992 to 2008. *Note*: The data is collected in-person from Hydrocarbon Development Institute of Pakistan (HDIP), Government of Pakistan, Islamabad.

Table 2
Macro social accounting matrix of Pakistan for 2008 (unit: Rs. 'Billion').
Sources: FBS (2001) and authors' calculations by using data from Dorosh et al. (2006), FBS (2008, 2009, 2011), FD (2008, 2009, 2010), SBP (2008, 2010a, 2010b, 2012), FBR (2009), HDIP (2010), Debowicz et al. (2012a), and the data collected in-person from Federal Bureau of Statistics (currently: Pakistan Bureau of Statistics) and Hydrocarbon Development Institute of Pakistan (HDIP), Government of Pakistan, Islamabad.

Receipts	Expenditures								
	Industries	Products	Labor	Capital	Household	Government	S–I	ROW	Total
Industries		18,405						1201	19,606
Products	9,486				8061	1295	2259		21,101
Labor	2,779								2,779
Capital	6,404								6,404
Household			2779	5728		606		769	9,881
Government	171	150		442	391			28	1,182
S–I	767				1429	(7 7 7)		840	2,259
ROW		2,545		234		58			2,837
Total	19,606	21,101	2779	6404	9881	1170	2259	2837	

4. Preparation of the database

4.1. Input–output table and SAM

Data availability is the cornerstone in designing a CGE model and determining the extent of details to which an economy can be analyzed (Oladosu and Rose, 2007). A Social Accounting Matrix (SAM) which usually serves as a database for a CGE model is a matrix presentation of interrelationships between an input–output table, a coherent arrangement of supply and use of goods and services in an economy, and other institutional sector accounts (UNSD, 1994). In Pakistan, history of input–output table compilation remained very unfortunate in the last two decades. Federal Bureau of Statistics—FBS (currently: Pakistan Bureau of Statistics) is Pakistan's official statistical organization which is responsible for compilation of different socio-economic statistics including the input–output tables. There are a total of three input–output tables developed since its inception, including: a pilot 1984–1985 table produced under the support of a Dutch Government funded project, a 1989–1990 table, and a 1990–1991 table produced independently by the staff of FBS (FBS, 2001).

Lack of an input–output table in the recent years has badly hampered any efforts in the arena of CGE modeling in Pakistan. A few individual attempts are though made to update the old 1990–1991 table for more recent years such as Dorosh et al. (2006), but still the possibility to incorporate the latest available information in inter-industrial consumption especially for energy sectors which showed huge dynamics in the past decade or so could not be realized (historical energy consumption trend of the country in the last two decades is shown in Fig. 3). This study, therefore, attempted to utilize the most requisite updated inter-industry transactions along with other parameters of the input–output table for environmental policy analysis of Pakistan.

The row and column wise iterative procedure, commonly known as RAS (see e.g. Eurostat, 2008 and Miller and Blair, 2009 for detailed discussion on RAS) could not be followed in this analysis, mainly due to uneven sectoral energy consumption changes. Thus, manual adjustments are made to update the intermediate consumption matrix by using monitory and physical energy consumption data from different sources such as FBS (2009), HDIP (2010) etc. For a few sectors where latest data could not be constructed for the benchmark year, old input–output coefficients are used as the last resolve to drive their inter-industry consumptions. Other parameters in the input–output table which are also updated for 2008, included: (1) labor wages and capital rentals, (2) taxes, tariffs and subsidies on production, (3) imports and exports, (4) final consumption, and (5) fixed and inventory investment, by using data collected in-personal from Federal Bureau of Statistics (FBS) and from different reports of the government agencies responsible for compilation of these statistics (FBS, 2008, 2009, 2011; SBP,, 2008, 2010a 2012; FD, 2008, 2009, 2010; FBR, 2009; HDIP, 2010). The social accounting matrix or SAM for 2008 is then derived by combining the input–output table with the institutional sector accounts data obtained from (Dorosh et al., 2006; FD, 2010; SBP, 2010b; Debowicz et al., 2012a). The macro structure of the SAM used in this analysis is shown in Table 2.

4.2. Factor endowments

Pakistan does not compile fixed capital stock accounts. We used the database of physical capital stock estimates for 92 developing and industrial countries including Pakistan from 1960 to 1990 by Nehru and Dhareshwar (1993) of the World Bank as a reference point to establish these accounts for this study. Since these estimates are based on 1987 constant local prices, this year is considered as an opening entry and estimates for the following years are obtained by adding new fixed investment during the period, taken from SBP (2010a), in the previous year capital stock depleted at a rate of 5% which is assumed based on the depreciation rates used in LSMI 2005–2006 (FBS 2009), energy data collected in-person from FBS and old 1990–1991 input–output table of the country. All the estimates are revalued to 2008 by using GDP deflator to get the capital stock at current value of the benchmark year. This method is a very reflection of the Perpetual Inventory Method (PIM) proposed by United Nations (UNSD, 1994) to estimate existing stock of fixed assets, which also produced quite similar results when used with the same 5 years of average service life for all the past investment. Sector-wise disaggregation of capital stock is done based on the GFCF shares for the last 25 years and capital rental rates.

Besides physical capital stock, labor force was also needed to estimate. To achieve this end, the population falling under the age group of 15–59 is considered a good proxy of the labor force and therefore used to project it for the stipulated time period of the study. The population data for 1980 to 2050 and labor force data for 1980 to 2008 which are used for the projections are taken from FD (2012) and UNPD (2012), respectively. The employed persons distribution by Industry for 2008, obtained from (SBP, 2010a), and sectoral wage rates are used to distribute the labor force among the sectors.

The model assumes full employment of factors of production: labor and capital; similar formulation can be found followed by many other recent analyses such as Lu et al. (2010), Dai et al. (2011) etc.

4.3. Other data inputs

The parameters that are decided both exogenously and inside the model by using SAM and other data inputs and elasticity values are main constituents of the database used to construct the TECGE model. The private, government, and foreign savings rates are exogenously updated to account for the government projections, though not that much ambitious, envisioned in its long-term policy perspectives. The private saving, for example, is viewed very inadequate to meet the even current low level of investment, while foreign saving is predicted equaling to at least 5% of the GDP. The government savings or current account balance which is currently negative is sought to improve through various proposed reforms over the period (PC, 2007).

Primary factor (labor, capital) annual productivity growth rates are also imposed exogenously, differentiated across industries. However, it is made certain that overall factor productivity growth does not deviate much from the stipulated 0.5% during 2009–2014 and 1% between 2015 to 2050 per annum (due to the present dismal economic condition of the country, the rates are assumed half for the period 2009–2014 of those used for 2015–2050).

For scale and share parameters in CES and CET functions in production and trade modules, calibration method is employed; which assumes initial or benchmark equilibrium to derive these parameters so as the model can reproduce this initial data set as a solution (Shoven and Whalley, 1984). The elasticity parameters used in the model consist of the substitution/transformation elasticities used in the production and external sectors. Lack of the requisite time series or cross sectional data as well as time and other resource constraints almost left it impossible to estimate values of the elasticity parameters for this study. Therefore, relevant existing literature (Bohringer and Rutherford, 1997; Naqvi, 1998; Timilsina and Shrestha, 2006; Fæhn et al., 2009; Labandeira et al., 2009; Wang et al., 2009; He et al., 2010; Debowicz et al., 2012b) is used to define appropriate values for these parameters, which are presented in Appendix B of this study.

5. Simulations and discussion

5.1. Scenario formulation

As suggested by Keohane et al. (1997), "…it is fundamental to consider the indirect incentives that may arise from the use of fiscal revenues. Indeed, without any redistribution of fiscal revenues, carbon taxes impose a higher cost to polluters than command-and-control policies or emissions trading systems with free initial allocation of permits." (quoted in Baranzini et al., 2000). Similarly, in a more recent publication (Bor and Huang, 2010), it is asserted that levying an energy tax not necessarily lead to negative economic impacts, but the actual effects depends on complementary measures whether or not they are in place. Hence, it seems imperative for any environmental analysis based on climate taxes to coincide with other supplementary policies particularly involving revenue recycling that might based on either the tax neutrality principle or as the case may be. By taking into account the current domestic fiscal situation of the country, in the present study two broad policy scenarios, in addition to the base case scenario which is assumed operating without any climate regulations, are introduced. The first scenario (referred hereafter as Scenario T) involves solely the carbon tax shock to the economic system, whereas in the second scenario (referred hereafter as Scenario TE) a joint impact of carbon tax and energy efficiency improvement is simulated.

In the carbon tax scenario, two alternative cases are introduced which describe the way the extra tax revenue is treated. Case 1 represents levying climate tax at different levels such as \$20, \$30, \$40, \$50, \$60, \$70, and \$80 per ton of CO_2 and the tax revenue is entirely assigned to finance government consumption expenses in order that the pre-tax budget deficit remains constant. Conversely, in case 2, the additional tax recycling measure is employed and a CO_2 tax of \$50 is simulated with lump-sum transfer of the tax revenue to households as subsidy. Since going along the former case can not only improve fiscal health but also the imbalances of the system where some sectors are highly taxed on the expense of the others, as is the case for electricity sector which not only contributes a very insignificant but is highly subsidized from the public exchequer (the electricity sector received subsidies of Rs.102.24 billion or 29.5% of the total in the year 2008; whereas according to (IEA, 2010c), its contribution in CO_2 emission was estimated nearly 41% of the total emissions from fuel combustion), more emphasize is placed in the second scenario to analyze the tax impact by keeping the additional tax revenue with the government. Thus, in the two cases included in the Scenario TE, different levels of energy efficiency/productivity improvement are simulated, with a CO_2 tax of \$50 and tax revenue is treated as fiscal revenue used for the government consumption.

In Pakistan, the energy efficiency in the backdrop of energy supply and security issues is getting immense importance. In its long term perspective document "VISION 2030", the Government of Pakistan envisaged a lower ratio of primary energy to GDP growth rates primarily resulting from improved energy efficiency, which would consequently help to curtail long term energy requirements and restrict GHG emissions of the country (PC, 2007). Similar positive observations regarding potential gains in terms of energy savings that can be realized from energy efficiency improvements are put forward in the New Growth Framework or

NGF (PC, 2011). However, the government did not come out in its any medium/long term development frameworks with quantitative targets for the future for its energy efficiency improvement interests. This study, therefore, sets different energy efficiency improvement targets for base-run, which is usually referred as Autonomous Energy Efficiency Improvement (AEEI) and occurs naturally without any specific cause such as innovation process etc., and for policy scenario TE to investigate its impacts in coordination with CO_2 tax, the climate tax selected for this analysis.

Both the AEEI and policy oriented technology progress rates for energy are modeled exogenously. The rates in the base-run, as described in Table 3, corresponds to both electricity and primary energy inputs: oil, gas, and coal. However, in scenario TE, the efficiency improvement is only introduced to primary energy inputs, where it is chosen to increase 25% and 50% equally for oil, gas, and coal in the two cases, compared to the base-run scenario, between the periods 2015 to 2050, the period selected for policy simulations in this analysis. Another possibility would be to include electricity in the policy simulations for scenario TE. But, to be strictly adhere to the core of the analysis which defines coordinated investigation of taxation and efficiency policies and the fact that supply-side electricity efficiency will also improve-with improvements in the efficiency of fossil fuel based electricity generation units, as per 2008 estimates Pakistan generated almost 67% of its total electricity from thermal sources (SBP, 2010a), it was not preferred to reconsider it for any further energy efficiency policy shock in the present analysis.

The climate tax is also assumed implemented from 2015, voluntarily, as Pakistan being a developing country does not bear any international obligations so far to reduce or restrict its GHG emissions at any level (since carbon tax is modeled as a CO_2 tax, both should be considered synonymous whenever referred in this study). Detailed definitions of the scenarios and cases included in this study are given in Table 3.

5.2. Empirical results

This section explores macroeconomic and sectoral effects of carbon taxation and energy efficiency policy implementations. The main findings of the analysis are presented in terms of GDP, pollutant emissions, energy consumption, international trade and other relevant variables.

With regard to the case 1 of scenario T (will be referred hereafter as scenario T1) where we simulated carbon tax at different levels by assigning the tax revenue entirely to finance government consumption, changes in some of the macroeconomic variables such as GDP (calculated by using expenditure approach as described in Appendix A) household and general government consumptions, investment, imports and exports, energy consumption and pollutant emissions etc. compared with the base case scenario are shown in Table 4. As can be seen, the impact of carbon tax on Pakistan economy will be negative, but resulting reductions in energy consumption and pollutant emissions will be relatively higher. For example, for a carbon tax of $80 per ton of CO_2, GDP will decrease by 3.59% from the base case in 2050, compared to the substantial overall fall of 27.92% for primary energy consumption – the energy intensity of GDP, calculated as a ratio of real GDP to total primary energy consumption, is estimated to decrease by 25.24% – and 28.67% for CO_2 emissions. That is, for every 1% CO_2 emissions reduction, for example, there will be a cost of 0.13% of GDP reduction to the country. However, it is observed that the relative GDP loss at lower tax rates is much smaller than the higher tax rates (e.g. for a carbon tax of $10, a 1% CO_2 emission

Table 3
Scenarios for CGE model simulation.

Simulation schemes		Annual energy efficiency change rates (%)[a]	Emission tax rate[b]	Revenue assigned to:	
				Government (fiscal revenues)	Households (lump-sum transfers)
Base case		P1:.05, P2: 1.0	None	–	–
Scenario T	Case1	P1:.05, P2: 1.0	$10–$80 per ton of CO_2	Yes	–
	Case2	P1:.05, P2: 1.0	$50 per ton of CO_2	–	Yes
Scenario TE	Case1	P1:.05, P2: 1.25	$50 per ton of CO_2	Yes	–
	Case2	P1:.05, P2: 1.50	$50 per ton of CO_2	Yes	–

[a] P1 and P2 represent the periods 2008–2014 and 2015–2050, respectively.
[b] The average exchange rate in 2008 was approximately Rs. 62.5/$ (SBP, 2010a); so, for example, a tax rate of $50 per ton of CO_2 is equivalent to Rs. 3125 per ton of CO_2.

Table 4
Percent changes from the base case in the selected key indicators in 2050 in CO_2 tax scenario under different tax rates.

Macroeconomic indicators	$10	$20	$30	$40	$50	$60	$70	$80
Gross domestic product (GDP)	−0.44	−0.90	−1.36	−1.82	−2.28	−2.72	−3.16	−3.59
Private consumption	−0.93	−1.82	−2.66	−3.46	−4.23	−4.98	−5.69	−6.38
Government consumption	4.73	8.78	12.37	15.60	18.58	21.34	23.93	26.37
Fixed investment (GFCF)	−0.83	−1.63	−2.40	−3.14	−3.87	−4.56	−5.24	−5.90
Inventory/stock investment	−1.01	−1.95	−2.84	−3.70	−4.52	−5.30	−6.06	−6.79
Aggregate exports	−1.16	−2.22	−3.21	−4.13	−5.01	−5.85	−6.65	−7.42
Aggregate Imports	−1.13	−2.17	−3.14	−4.06	−4.92	−5.75	−6.54	−7.30
Domestic production	−0.80	−1.56	−2.28	−2.98	−3.64	−4.28	−4.90	−5.50
Domestic demand	−0.82	−1.60	−2.34	−3.05	−3.73	−4.39	−5.02	−5.63
Primary energy consumption	−6.38	−11.33	−15.32	−18.63	−21.44	−23.87	−26.01	−27.92
Carbon dioxide (CO_2) emissions	−6.69	−11.79	−15.88	−19.25	−22.10	−24.57	−26.74	−28.67
Nitrous oxide (N_2O) emissions	−5.02	−8.99	−12.30	−15.15	−17.67	−19.93	−21.99	−23.89
Methane (CH_4) emissions	−8.70	−15.07	−19.96	−23.84	−27.03	−29.70	−32.00	−33.99
Sulfur dioxide (SO_2) emissions	−8.71	−14.85	−19.54	−23.31	−26.44	−29.13	−31.48	−33.56
Energy intensity of GDP	−5.97	−10.52	−14.15	−17.12	−19.61	−21.74	−23.60	−25.24

Table 5
Percent changes from the base case in sectoral output in 2050 in CO_2 tax scenario under different tax rates.

Production sectors	\$10	\$20	\$30	\$40	\$50	\$60	\$70	\$80
Agriculture	−0.55	−1.10	−1.63	−2.15	−2.66	−3.15	−3.64	−4.11
Crude oil and natural gas	−1.36	−2.57	−3.68	−4.70	−5.66	−6.57	−7.43	−8.26
Other minerals	−0.97	−1.88	−2.73	−3.55	−4.33	−5.08	−5.81	−6.51
Food and beverages	−0.81	−1.58	−2.32	−3.03	−3.71	−4.37	−5.01	−5.64
Textile and Wearing apparel	−0.94	−1.83	−2.68	−3.50	−4.28	−5.03	−5.75	−6.46
Paper, wood and furniture	−1.03	−1.99	−2.91	−3.79	−4.62	−5.43	−6.20	−6.94
Chemical products	−0.79	−1.56	−2.31	−3.05	−3.77	−4.47	−5.16	−5.83
Basic Metal products	−0.95	−1.89	−2.80	−3.70	−4.58	−5.44	−6.28	−7.10
Fabricated metal products	−0.56	−1.10	−1.63	−2.15	−2.66	−3.16	−3.65	−4.13
Non-metallic mineral products	−4.07	−7.46	−10.35	−12.87	−15.10	−17.10	−18.91	−20.56
Electrical machinery	−0.68	−1.35	−2.01	−2.65	−3.28	−3.89	−4.49	−5.08
Non-electrical machinery	−0.56	−1.13	−1.70	−2.28	−2.86	−3.43	−4.00	−4.56
Other manufacturing products	−1.36	−2.57	−3.68	−4.72	−5.69	−6.60	−7.47	−8.30
Coal Products	−7.23	−12.35	−16.20	−19.24	−21.71	−23.76	−25.50	−27.01
Petroleum products	−0.59	−1.35	−2.23	−3.19	−4.21	−5.26	−6.33	−7.42
Gas supply	−8.70	−15.48	−20.87	−25.24	−28.85	−31.89	−34.48	−36.71
Electricity	−2.60	−5.00	−7.22	−9.29	−11.25	−13.09	−14.84	−16.51
Construction	−0.76	−1.52	−2.25	−2.97	−3.68	−4.37	−5.04	−5.69
Transport services	−0.99	−1.95	−2.87	−3.77	−4.63	−5.47	−6.28	−7.07
Other services	0.04	0.01	−0.06	−0.16	−0.27	−0.39	−0.53	−0.67

reduction can be achieved only for an approximately 0.07% of GDP loss). This shows rising marginal abatement cost, when measured in terms of GDP decline, with increase in total emissions reduction.

Since climate policies aimed at reducing emissions of any particular pollutant might also produce ancillary benefits in terms of reduction in other pollutants, the present study therefore calculates emissions reduction for the pollutants, namely: methane (CH_4), Nitrous oxide (N_2O), and sulfur dioxide (SO_2). In the base case, the emissions of CH_4 and N_2O are estimated to grow to approximately 119.0 and 19.7 thousand tons in 2050, starting from 14.0 and 2.3 thousand tons in the base year, respectively. Similarly, the SO_2 emissions which are estimated nearly 1.4 million tons in the benchmark year increase to 12.1 million tons in 2050. In the policy scenario T1, all these pollutant emissions decrease considerably. The CH_4 emissions for a tax of \$80 decrease by 33.99%, N_2O emissions by 23.89% and SO_2 emissions by 33.56% from the base case. As is evident, the magnitude of reduction in CH_4 and SO_2 emissions is relatively high, which can be explained by the fact that coal which largely contributes in their emissions is much cheaper followed by natural gas and to a long way oil and therefore bears comparatively more burden of the climate tax (as per our calculations, the economy-wide prices of oil, gas, and coal stood at Rs. 50.2, 9.4, and 7.4 thousands per TOE respectively in the benchmark year); the coal consumption, for a tax of \$80, declines by 47.03%, compared to 36.71% reduction in gas and 9.12% in oil consumption. The higher rate of SO_2 emissions reduction in this case also rules out any trade-off between treating local and GHG emissions and thus signifies the need, as pointed out by Xu and Masui (2009), to view the emission control policies comprehensively and in a wider spectrum.

Changes in the private and government final consumptions are expected quite different mainly due to the TECGE model specification for allocating the additional tax revenues. For a tax of \$80, the private consumption reduces to a significant 6.38%, whereas the government consumption increases by 26.37%. Since reducing emissions via carbon tax increases the domestic goods prices which ultimately reduce consumption demand, increase in the tax rate for every 10\$ (from 10\$ to 80\$) in TECGE model reduces private consumption on average by 0.78%. The increase in government consumptions, on the other hand, comes from extra available carbon tax income which is assumed entirely assigned to the government consumption expenditures. However, as suggested by Shoven and Whalley (1984) that the economy-wide welfare measure needed to include the welfare impact from changes in the level of provision of public goods and services, the household consumption/utility changes in the present study therefore be interpreted in this context.

The total investment that comprises fixed and inventory investment and determined by the total savings the economy can muster from public, private and foreign sources is found to decrease with imposition of carbon tax. The inventory investment is assumed relative to the sectoral production and therefore falls with reduction in sectoral outputs. The fixed investment, on the contrary, decreases due to reduced potential of economic agents during recession to generate enough savings to sustain the previous investment level of the economy. Similarly, the aggregate exports and imports also decrease. The exports fall because of increased domestic production costs which leave domestic goods less competitive in the face of foreign goods, while imports decrease mainly due to reduced domestic energy goods demand and consequently imports which in the base year constituted nearly 27% of the total imports of the country. The domestic production which is composed of domestic production for domestic market and exports, and domestic demand which included domestic production for domestic market and imports are estimated to decrease, for a carbon tax of \$80, at 5.50% and 5.63%, respectively, from the base case.

Regarding sectoral impact, the extent of upward shift of sectoral marginal cost functions due to emission taxation, as stated by Oladosu and Rose (2007), may varies with the energy share in production as well as substitution possibilities among energy sources and between energy and other inputs. The impact of carbon tax on sectoral output under different rates for this study is presented in Table 5. As can be seen, the carbon tax mainly affects the output of coal, gas and electricity along with highly energy intensive 'Non-metallic mineral products' sector. A carbon tax for \$80, for example, would cause a reduction of approximately 27.01% in coal, 36.71% in gas, 16.51% in electricity, and 20.56% in 'Non-metallic mineral products' industries. The higher reduction in the output of coal and gas sectors is obvious to be expected because carbon tax will increase fossil energy goods prices which eventually decrease their consumption demand. However, for the petroleum products which are expected to bear relatively less impact of carbon taxation, the output is estimated to reduce by merely 7.42%. The 'textile and wearing apparel' sector which being an agriculture economy falls under traditional industries of Pakistan (PC, 2007) and constituted nearly 56% of the total exports in the base year, its output is found to decrease by 6.46%. The output of "Other services" sector is expected to be least affected, with

Table 6
Comparison between different policy scenarios for some key macroeconomic variables (percent changes from the base case in 2050).

Macroeconomic indicators	Scenarios			
	ST1	ST2	ST3	ST4
Gross domestic product (GDP)	−2.28	−1.47	−1.10	0.04
Private consumption	−4.23	−1.57	−2.97	−1.74
Government consumption	18.58	−1.51	18.33	18.09
Fixed investment (GFCF)	−3.87	−1.98	−2.66	−1.50
Inventory/stock investment	−4.52	−2.72	−3.74	−3.00
Aggregate exports	−5.01	−3.57	−4.45	−3.91
Aggregate Imports	−4.92	−3.53	−4.27	−3.63
Domestic production	−3.64	−2.51	−2.83	−2.04
Domestic demand	−3.73	−2.59	−2.92	−2.13
Primary energy consumption	−21.44	−20.18	−23.44	−25.38
Carbon dioxide (CO_2) emissions	−22.10	−20.83	−24.03	−25.90
Nitrous oxide (N_2O) emissions	−17.67	−16.21	−20.29	−22.85
Methane (CH_4) emissions	−27.03	−25.91	−28.57	−30.07
Sulfur dioxide (SO_2) emissions	−26.44	−25.07	−28.76	−31.01
Energy intensity of GDP	−19.61	−18.98	−22.58	−25.41

positive percent changes for the tax rates of \$10 and \$20 and slightly negative when the tax rate is assumed to be imposed with higher rates. This is because of the increased general government spending for public services, which is one of the main constituents of this sector. For the remaining sectors, however, the percent changes in the sectoral outputs would be more or less identical. The diverse changes within energy and other non-energy sectors, thus, indicate that emissions reduction through carbon taxation in the country would cause energy shift and structural changes in industries (Note: to avoid unnecessary duplication of arguments, the sectoral effects for household consumption, international trade etc. in scenario T1 are left to be discussed with other policy scenario options in the following segments of the analysis).

Next, the macroeconomic impacts under second case of scenario T (will be referred hereafter as scenario T2) where a carbon tax of \$50 is employed and tax revenue is returned to households in lump-sum fashion, and scenario TE (the two cases in this scenario will be referred hereafter as scenario TE1 and scenario TE2, respectively) where carbon tax and energy efficiency improvement are jointly simulated are presented in Table 6, in comparison with scenario T1 at carbon tax rate of \$50. The results show a decrease of 2.28% in GDP in scenario T1 when carbon tax revenue is used for fiscal adjustments and considerably moderate 1.47% when it is returned to household in lump-sum fashion. The positive difference in scenario T2 arises partly from increased investment or MPS (marginal propensity to save) which ensures that for any additional private income a certain part must be saved for the future investment and partly from comparatively increased consumption for all production sectors of the economy. The relative effectiveness of the tax for both the cases will be sufficiently high. The CO_2 emissions, for instance, would decrease by 22.10% and 20.83%, respectively, for the two cases, thus inflicting GDP loss of merely 0.10% and 0.07% for every 1% decrease in CO_2 emissions.

Impacts of joint tax/efficiency policy in the second scenario (scenario TE) are, however, quite different. The two cases included in this scenario are simulated for different energy (oil, gas, and coal) efficiency improvement rates with a carbon tax of \$50, and treating the tax revenue as fiscal revenue for government consumption. Since energy efficiency improvement can generates effects identical to an increase in physical energy inputs and reduction in the implicit or effective energy prices (Hanley et al., 2009), the overall energy price effects in the system after coordinated implementation of carbon tax and energy efficiency stimuli will depend on the interaction of two factors: increase in energy prices due the assigned cost for their polluting potential

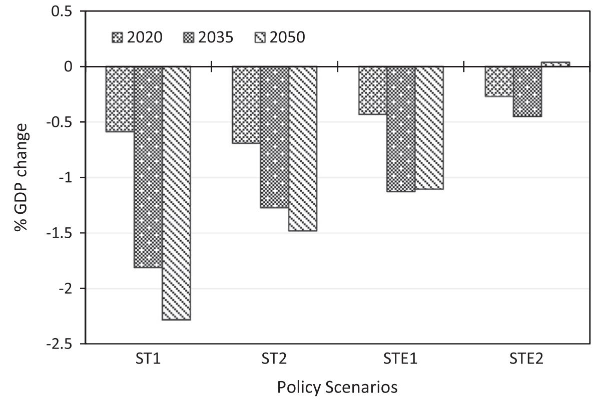

Fig. 4. Percent changes in Gross domestic product (GDP) from the base case under different carbon tax/energy efficiency policy scenarios.

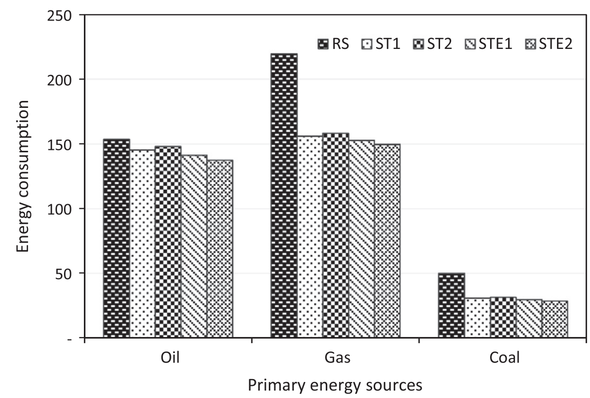

Fig. 5. Total primary energy consumption (million toe) in the year 2050 under the base case and different carbon tax/energy efficiency policy scenarios.

(emissions taxation) and decrease in the implicit energy prices that will be observed in the economy due to rising productive capacity of the energy sources. Hence, energy costs for the users (production firms in this case) will now become a function of energy input prices, additional emission costs linked to per unit of energy, and energy efficiency improvement, which can be expressed in the following equation:

$$\text{Energy costs} = \frac{(\text{energy input prices} + \text{additional emission costs})}{\text{energy efficiency improvement}}$$

GDP under this scenario grows positive compared to the scenario T1, as energy efficiency improvement gradually offset the deteriorating effects caused by the emission taxation. It is observed to change at −1.10% and 0.04% from the base case with substantial decrease of 23.44% and 25.38% for total energy consumption and consequently 24.03% and 25.90% reductions in CO_2 emissions for the two cases, respectively. Similar changes are expected for other pollutant emissions. An important policy implication in this case is that the coordinated approach in Pakistan can help improve demand reductions for highly imported and therefore relatively more expensive oil. This would happen because least price changes for oil due to carbon taxation, as explained earlier, will encourage the efficiency improvement to be implemented with its full potential both from output and price sides. Thus, oil demand that only reduces 5.4% in scenario T1 almost doubled to 10.6% in scenario TE2, compared to the reductions for gas at 28.9% and 31.8%, and for coal at 38.1% and 42.5%, respectively, in the two scenarios (percent changes in GDP over time along with total energy consumption predicted by TECGE model for the scenarios T & TE are shown in Figs. 4 and 5, respectively).

The aggregate private consumption is estimated to reduce by 4.23% and 1.57% in scenarios T1 & T2, respectively. In the former case the effect of price rise due to emission taxation fully shifts to consumers without any compensation and therefore generates equivalently high impact on their demands. However, this negative impact would significantly decrease in scenario TE where tax impact in the production sectors is offset by the corresponding energy efficiency stimulus. For government consumption, it decreases only in scenario T2 where revenue neutrality principle is followed. The reduction can be attributed to GDP contraction which would consequently lead to the decline in revenue collection potential of the economy. Again, the decrease in private consumption should not be viewed in isolation from increase in government expenditures. Regarding fixed and inventory investment, both are expected to decrease in all the scenarios but changes in fixed investment rather show a slightly positive trend in scenario TE, which mainly occurs due to increased GDP and private income which are further meant to bolster private or household savings. Other aggregate variables such as exports, imports, and domestic production/demand demonstrate similar changes in the four scenario schemes as in private consumption but differ in magnitude.

Sectoral changes in output and household consumption are presented in Table 7. The output changes in scenario T2 when compared with scenario T1 are quite similar with exception that rates of change are relatively small. However, in the two cases of scenario TE, the situation is fairly different. Here, though non-energy sectors also show less output decrease than in scenario T1, output of energy sectors further decreases due to reduced energy demand caused by the increased energy productivity. The oil, gas, and coal outputs in scenario TE2, for example, are expected to reduce at the rates of 8.71%, 31.82%, and 28.40%, than 4.21%, 28.85%, and 21.71% reductions in scenario T1, respectively. The output of 'textile and wearing apparel' sector would fall by 3.6% in scenario TE1 and substantially lower 2.96% in scenario TE2, compared to 4.28% in scenario T1.

For the final private consumption, the most significant impact of carbon tax is observed for the 'non-metallic mineral products' and electricity. The former would likely incur a reduction of 19.38% and 17.72% while the later a reduction of 12.87% and 10.41% in scenarios T1 & T2, respectively. The average reduction for all the remaining sectors is estimated at 3.30% and 1.11% for the two cases, respectively. In scenario TE, the negative impacts associated with the carbon tax in terms of decreased final consumption are observed to be sufficiently reduced. The electricity consumption, for example, would suffer a loss of 8.47% in the first case, which will further reduce to merely 4.1% in the second case. Similarly, for 'non-metallic mineral products' the consumption is projected to decrease at 16.24% and 13.16% in the two cases, respectively.

Regarding international trade, the sectoral effects of carbon tax and its joint simulation with energy efficiency improvements are presented in Fig. 6. As can be seen, the highest export reductions in the tax scenarios are observed for highly energy-intensive non-metallic mineral products, while the highest import reductions are for energy goods such as coal and 'crude oil and natural gas', and other minerals. The results also show that exports of 'textile and wearing apparel' would decrease by 4.50% and 3.40% in scenarios T1 & T2, with increase in domestic mining sectors as their domestic demand would decrease significantly. Imports of petroleum products would fall by 6.19% and 4.68% in scenarios T1 & T2, respectively; which will further contribute in enhancing the energy security of the country. Alternatively, in scenario TE, the exports of all goods and services are found to improve as energy efficiency growth would be able to lessen the competitiveness loss caused by the carbon tax. Similarly, imports would also reduce except for energy goods, oil and coal, as their demand will further decline with improvement in energy efficiency in the economy.

6. Sensitivity analysis

Since sensitivity analysis is key to define robustness of the results of a CGE analysis, additional simulations are carried out in this study by employing low and high elasticity cases obtained by reducing (augmenting) the elasticity values by an arbitrary 20%. The parameters selected for the test include:

- substitution elasticity between value added and energy composites (σ^{vae}),
- substitution elasticity between fossil energy composite and electricity (σ^{en}),
- Armington CES composite elasticity (σ^{c}), and
- transformation elasticity (σ^{t}).

Table 7
Percent changes from base case in sectoral output and private consumption in 2050 under scenario T & TE.

Production sectors	Sectoral output				Private consumption			
	ST1	ST2	STE1	STE2	ST1	ST2	STE1	STE2
Agriculture	−2.66	−0.72	−1.94	−1.25	−2.85	−0.89	−1.92	−1.02
Crude oil and natural gas	−5.66	−4.11	−6.28	−6.90	−1.35	0.62	0.67	2.66
Other minerals	−4.33	−2.99	−3.28	−2.27	−1.18	0.51	−0.43	0.28
Food and beverages	−3.71	−1.10	−2.80	−1.91	−3.85	−1.31	−2.77	−1.74
Textile and Wearing apparel	−4.28	−2.84	−3.60	−2.96	−4.07	−2.01	−2.77	−1.52
Paper, wood and furniture	−4.62	−2.96	−3.44	−2.29	−3.99	−1.80	−2.80	−1.65
Chemical products	−3.77	−2.04	−2.53	−1.34	−3.50	−1.45	−2.08	−0.71
Basic Metal products	−4.58	−3.44	−3.46	−2.40	−4.18	−2.21	−2.78	−1.43
Fabricated metal products	−2.66	−1.36	−2.14	−1.64	−3.20	−1.09	−2.08	−1.00
Non-metallic mineral products	−15.10	−13.91	−12.98	−10.86	−19.38	−17.72	−16.24	−13.16
Electrical machinery	−3.28	−1.46	−2.19	−1.15	−3.88	−1.73	−2.52	−1.21
Non-electrical machinery	−2.86	−1.76	−1.70	−0.59	−3.97	−1.84	−2.56	−1.19
Other manufacturing products	−5.69	−3.73	−4.65	−3.64	−5.15	−2.94	−3.89	−2.67
Coal Products	−21.71	−21.48	−25.15	−28.40	−3.48	−1.34	−2.08	−0.72
Petroleum products	−4.21	−2.06	−6.46	−8.71	−2.98	−0.48	−1.21	0.51
Gas supply	−28.85	−27.91	−30.36	−31.82	2.74	4.50	4.41	6.05
Electricity	−11.25	−9.44	−7.50	−3.78	−12.87	−10.41	−8.47	−4.10
Construction	−3.68	−2.30	−2.74	−1.83	−4.27	−2.52	−3.20	−2.17
Transport services	−4.63	−3.28	−3.07	−1.54	−5.71	−3.87	−2.99	−0.34
Other services	−0.27	−1.23	0.32	0.90	−4.58	−0.12	−3.76	−2.96

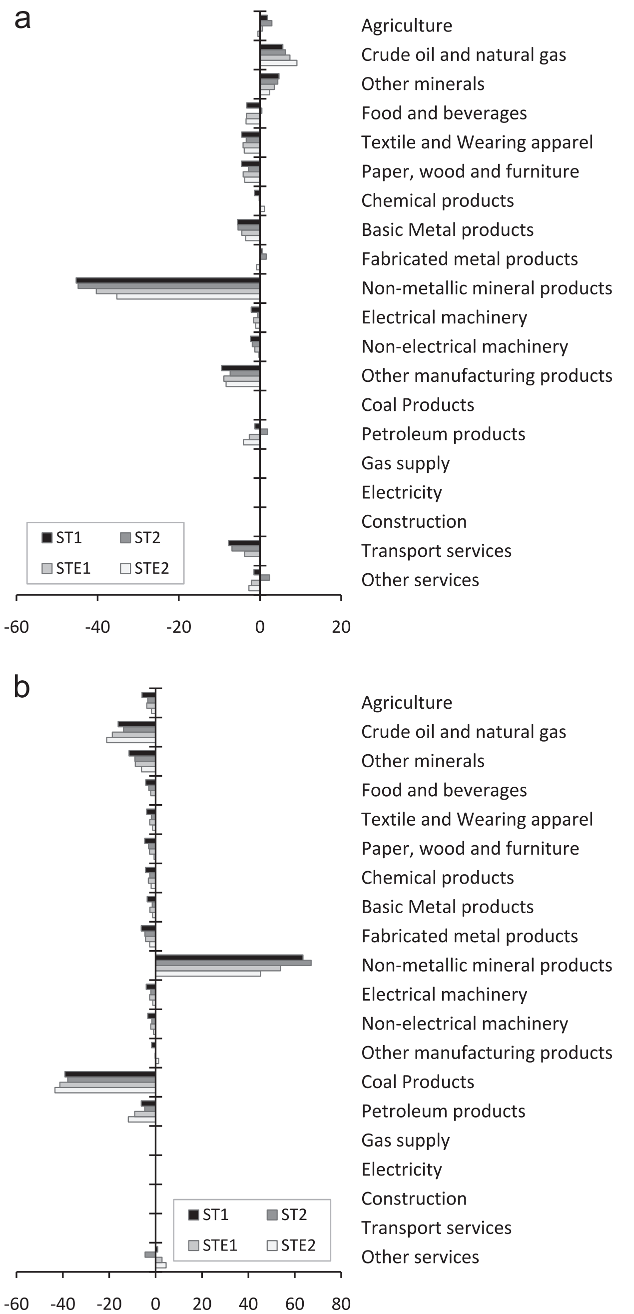

Fig. 6. Percent changes in (a) exports and (b) imports from the base case under different carbon tax/energy efficiency policy scenarios in the year 2050.

The results of the sensitivity analysis for the first case of both carbon tax incidence and joint approach of carbon tax and energy efficiency improvement for demonstration purpose are given in Table 8. As can be seen, the selected variables, GDP, CO_2 emissions, exports, and imports, are not found sensitive to changes in σ^c, σ^t, and σ^{en}, but CO_2 emissions are quite dependent on the elasticity selected between primary factors (labor and capital) and energy goods (electricity and other fossil fuels), i.e. σ^{vae}. For example, in scenario T1, a drop (increase) of 20% in σ^{vae} from its base value would cause fall in CO_2 emissions to change from 22.10% to 20.54% (23.63%) from the base case. Similarly, in scenario TE1, the CO_2 emissions would decrease by 22.89% (25.14%) compared to 24.03% with the original elasticity values used in the model. Apart from these changes in some of the variables arising due to use of different sets of elasticity values, the overall results are observed

Table 8
Sensitivity analysis results (unit: % changes from the base case values in 2050).

Parameter	Selected indicators	ST1			STE1		
		Actual	Low	High	Actual	Low	High
$\sigma^{(kl)e}$	GDP	−2.28	−2.14	−2.41	−1.10	−1.02	−1.19
	CO_2 emissions	−22.10	−20.54	−23.63	−24.03	−22.89	−25.14
	Exports	−5.01	−4.39	−5.65	−4.45	−3.99	−4.93
	Imports	−4.92	−4.35	−5.51	−4.27	−3.84	−4.71
σ^{en}	GDP	−2.28	−2.30	−2.25	−1.10	−1.12	−1.08
	CO_2 emissions	−22.10	−21.91	−22.30	−24.03	−23.86	−24.19
	Exports	−5.01	−5.06	−4.96	−4.45	−4.50	−4.41
	Imports	−4.92	−4.97	−4.87	−4.27	−4.32	−4.23
σ^c	GDP	−2.28	−2.29	−2.27	−1.10	−1.11	−1.10
	CO_2 emissions	−22.10	−22.14	−22.08	−24.03	−24.06	−24.00
	Exports	−5.01	−5.03	−4.99	−4.45	−4.50	−4.40
	Imports	−4.92	−4.94	−4.91	−4.27	−4.32	−4.23
σ^t	GDP	−2.28	−2.27	−2.28	−1.10	−1.10	−1.10
	CO_2 emissions	−22.10	−21.98	−22.23	−24.03	−23.93	−24.13
	Exports	−5.01	−4.98	−5.03	−4.45	−4.41	−4.48
	Imports	−4.92	−4.89	−4.94	−4.27	−4.23	−4.30

not to deviate very significantly from those inferred by the main analysis; and also, no qualitative change is observed. Thus, the results of the analysis can be viewed relatively robust around the current formulation of the model.

7. Conclusions and recommendations

Rapid increase of atmospheric GHG emission concentrations in the recent years has led analysts to investigate different mitigation policy options for their impacts on the economy and environment. The climate taxes (most commonly carbon or CO_2 taxes) and energy efficiency improvements are the two prominent policy instruments given due consideration for the purpose. The carbon taxes, though, have shown great potential to reduce GHG emissions, they usually incur GDP losses. Similarly, the energy efficiency improvement that generates the effects identical to an increase in physical energy inputs and reduction in implicit or effective energy prices accompany the perils of rebound or in some cases take-back effects. Since appropriate carbon/energy pricing can not only prevent fall of energy services costs emanating from increased energy efficiency which instigate the rebound/take-back effects but also reduces the negative economic effects associated with the climate taxes, it thus seems imperative to view these technology and relative price related policies as complementary. Against this background, this analysis tried to assess the impacts of carbon tax in isolation and jointly with energy efficiency improvement for a developing country, Pakistan.

A 20 sector recursive dynamic CGE model based on neoclassical approach is developed for simulations. Since the input–output table which provide foundation for construction of a SAM, the database for a CGE model, is not published in the recent years, as the latest available belongs to 1990–1991, special efforts are made to update it especially by incorporating the latest available inter-industrial energy consumption information for the benchmark year, 2008. The model is run until 2050, with policy measures starting from the year 2015.

Two policy scenarios are adopted in the study: a CO_2 tax scenario and a joint implementation of CO_2 tax/energy efficiency improvement scenario. In the first scenario (scenario T), two alternative cases are introduced which are distinguished by the manner the extra tax revenue is treated. That is, case 1 in which climate tax is levied at different levels ranging from \$10 to \$80 per ton of CO_2, the tax revenue is entirely assigned to finance government consumption expenses. Conversely, in case 2, the additional tax recycling measure is employed and a CO_2 tax of \$50 is simulated with lump-sum transfer of the tax revenues to households. In the second scenario (scenario TE), however, different levels of energy productivity growth for primary sources oil, gas and coal are simulated with a \$50 per ton of CO_2 tax, while treating the tax revenue for government consumption.

The findings of the analysis reveal that carbon tax can reduce harmful pollutant emissions such as CH_4, N_2O, and SO_2 along with CO_2 to a significant level, but with negative GDP impact. The CO_2 emissions for a tax of \$80, for example, would decrease up to 27.92% in 2050 with an estimated fall of 3.59% in real GDP of the country. However, it is observed that the relative GDP loss at lower tax rates is much smaller than the higher tax rates. Other macroeconomic variables such as private consumption, investment, aggregate exports and import etc. are also expected to decrease, except the government consumption which increases significantly with rise in the tax rate.

Furthermore, a comparison between the first case of scenario T (under a CO_2 tax of \$50) and the other scenario schemes adopted in this analysis shows that GDP loss would be considerably moderate when the tax revenues are returned to households than keeping it for fiscal use. In the former case the GDP is expected to decrease only 1.47%, compared to 2.28% in the later case; with reduction in CO_2 emissions at 20.83% and 22.10% for the two cases, respectively. It is to mention here that the relatively high emission reductions in our case are largely consistent with those put forward by the studies focused on analyzing the climate tax impacts (see e.g. Wissema and Dellink, 2007; Telli et al., 2008; Lu et al., 2010). On the other hand, in scenario TE, the GDP is expected to grow comparatively positive with even higher reductions in energy consumption demand and so pollutant emissions. It is observed to change at -1.10% and 0.04% with substantial decrease of 23.44 and 25.38 in total energy consumption and 24.03% and 25.90% in CO_2 emissions for the two cases, respectively. This simultaneous economic as well as environmental improvement would thus have positive implications for the country regarding its sustainable development path where economic achievements would be able to follow cleaner environment and enhanced energy security with less import dependency of the country.

Also, an important revelation of the study explains that carbon taxes can reduce other especially local pollutant emissions (in this case SO_2) even at a higher rate than the emissions the tax is meant for, and therefore rules out any trade-off between local and GHG emissions control policies and thereby the urgency of focusing on either of the two.

It is important to note that regarding the tax policy, our results do not fall completely in line with the government's future fossil energy plans (similar divergence is indicated by Loisel, 2009). Based on the estimated 82 billion TOE coal resource potential of the country, though controversial and too optimistic from many corners, the government wants to expand the share of coal in total energy mix in general and in electricity generation in particular to replace the expensive imported crude oil and petroleum products. Increased role of gas in electricity generation is also earmarked to bring down oil share to a negligible below 5% (PC, 2005, 2007). Therefore, this study supports decrease in price disparity between the primary energy sources and deployment of clean coal options such as CCS to make coal a viable investment option under carbon constrained policy design against expensive but abundant renewable energy resource potential of the country.

8. Future research directions

We do not hesitate to acknowledge that this study, like many other climate tax and energy efficiency CGE studies, rests on some simplified assumptions, which should be kept in view while interpreting the results. The underlying assumptions of the analysis and possible future course for further research are as follows.

First, the benefits of cleaner environment due to carbon taxation, though considered highly uncertain by some authors such as Goulder (1995), especially for increased laborers' efficiency (also increased tourism and lower health bills etc., as mentioned by Xu and Masui, 2009) are not considered. Instead, only the impact on economic development is evaluated. Further, the energy efficiency improvement in the policy scenarios is modeled exogenous and costless, following Grepperud and Rasmussen (2004), Hanley et al. (2006), Anson and Turner (2009), Turner and Hanley (2011) and others, which might in reality involve cost implications. Since this analysis is designed based on the assumption of international technology transfer to promote energy efficiency improvement (see e.g. UNFCCC, 2008), which is also suggested as the least cost option (Rao et al., 2006), and the fact that to nullify the potential biased arising from this formulation, the energy efficiency improvement is spread over a longer horizon with small changes per year as opposed to a single policy shock, the results drawn thus make sense as for as this preliminary analysis is concerned (certainly, the time, data and financial constraints also apply here), and can be proved relevant for any further investigation considering even more complex systems with endogenous technological advancements.

Second, this study includes only a single representative consumer. As mentioned by Yang (2001) that the climate taxes affect labor and capital income differently, i.e. loss in the disposable income for the lowest income groups that derive large part of their incomes by providing labor and the highest income groups that generally own capital will not be identical. It will, thus, be sensible to distinguish between these consumer groups and analyze the impact of the tax for the possible 'regressivity' where lower income groups are disproportionately affected and 'progressivity' where higher income groups are supposed to bear relatively more tax burden. Additionally, for a country like Pakistan where income inequalities are rampant, as ratio of highest to lowest consumption share quintiles was estimated at 4.0 in 2007–2008 (FD, 2011), need for this type of analysis becomes even more fundamental and critical, and provide much broader insights regarding sustainable development path of the country ahead.

Lastly, as all the substitution and transformation elasticities used in this model were not available for Pakistan, standard approach is adopted and the elasticities are selected by surveying the relevant literature. It will be more pertinent, however, if in future these elasticities could be derived for the country which in turn can describe in a more clear way the interlinkages between economy, environment, and social development—the outcome generally intended from such studies.

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Appendix A. Formulation of the TECGE model

A.1. Model equations

A.1.1. Prices block

$$PM_{im} = PM_{im}^{w}\,(1+\tau_{im}^{mt})\,ER$$

$$PE_{ie} = PE_{ie}^{w}\,ER$$

$$PQ_i\,Q_i = PM_i\,M_i + PD_i\,D_i$$

$$PX_i\,X_i = PE_i\,E_i + PD_i\,D_i$$

$$PS_{s,i} = PQ_s + CP_{s,i}$$

$$PVAE_i\,VAE_i = PX_i[1-(\tau_i^{idt}-\tau_i^{sb})]\,X_i - \left[\sum_{ine} PQ_{ine}\,im_{ine,i}\right] INTC_i$$

$$PVA_i = 1/\beta_i^{va}\left[\alpha_i^{va\sigma_i^{va}}\,(R_i/e_i^{k})^{(1-\sigma_i^{va})} + (1-\alpha_i^{va})^{\sigma_i^{va}}\,(W_i/e_i^{l})^{(1-\sigma_i^{va})}\right]^{1/(1-\sigma_i^{va})}$$

$$PEN_i = 1/\beta_i^{en}\left[\alpha_i^{en\sigma_i^{en}}\,PFE_i^{(1-\sigma_i^{en})} + (1-\alpha_i^{en})^{\sigma_i^{en}}\,(PEL/e_i^{el})^{(1-\sigma_i^{en})}\right]^{1/(1-\sigma_i^{en})}$$

$$PFE_i = 1/\beta_i^{f}[\alpha_i^{f\sigma_i^{f}}\,PNSF_i^{(1-\sigma_i^{f})} + (1-\alpha_i^{f})^{\sigma_i^{f}}\,(PS_{coal,i}/e_i^{fc})^{(1-\sigma_i^{f})}]^{1/(1-\sigma_i^{f})}$$

$$PNSF_i = 1/\beta_i^{ns}[\alpha_i^{ns\sigma_i^{ns}}\,(PS_{oil,i}/e_i^{fo})^{(1-\sigma_i^{ns})} + (1-\alpha_i^{ns})^{\sigma_i^{ns}}(PS_{gas,i}/e_i^{fg})^{(1-\sigma_i^{ns})}]^{1/(1-\sigma_i^{ns})}$$

$$DEF = GDPN/GDPR$$

A.1.2. Production block

$$X_i = VAE_i\,/\,ivae_i$$

$$INTC_i = imc_i\,X_i$$

$$INT_{ine,j} = im_{ine,j}\,INTC_j$$

$$VAE_i = \beta_i^{vae}[\alpha_i^{vae}\,VA_i^{-\rho_i^{vae}} + (1-\alpha_i^{vae})\,EN_i^{-\rho_i^{vae}}]^{-1/\rho_i^{vae}}$$

$$VA_i = VAE_i\,[\beta_i^{vae-\rho_i^{vae}}\,\alpha_i^{vae}\,(PVAE_i/PVA_i)]^{\sigma_i^{vae}}$$

$$EN_i = VAE_i\,[\beta_i^{vae-\rho_i^{vae}}(1-\alpha_i^{vae})\,(PVAE_i/PEN_i)]^{\sigma_i^{vae}}$$

$$KD_i = VA_i\,[(\beta_i^{va}\,e_i^{k})^{-\rho_i^{va}}\alpha_i^{va}\,(PVA_i/R_i)]^{\sigma_i^{va}}$$

$$LD_i = VA_i\,[(\beta_i^{va}\,e_i^{l})^{-\rho_i^{va}}(1-\alpha_i^{va})\,(PVA_i/W_i)]^{\sigma_i^{va}}$$

$$FE_i = EN_i\,[\beta_i^{en-\rho_i^{en}}\alpha_i^{en}\,(PEN_i/PFE_i)]^{\sigma_i^{en}}$$

$$EL_i = EN_i\,[(\beta_i^{en}\,e_i^{el})^{-\rho_i^{en}}(1-\alpha_i^{en})\,(PEN_i/PEL)]^{\sigma_i^{en}}$$

$$NSF_i = FE_i\,[\beta_i^{f-\rho_i^{f}}\alpha_i^{f}\,(PFE_i/PNSF_i)]^{\sigma_i^{f}}$$

$$OIL_i = NSF_i\,[(\beta_i^{ns}\,e_i^{fo})^{-\rho_i^{ns}}\alpha_i^{ns}\,(PNSF_i/PS_{oil,i})]^{\sigma_i^{ns}}$$

$$GAS_i = NSF_i\,[(\beta_i^{ns}\,e_i^{fg})^{-\rho_i^{ns}}(1-\alpha_i^{ns})\,(PNSF_i/PS_{gas,i})]^{\sigma_i^{ns}}$$

A.1.3. Trade block

$$Q_{im} = \beta_{im}^{c}[\alpha_{im}^{c}\,M_{im}^{-\rho_{im}^{c}} + (1-\alpha_{im}^{c})\,D_{im}^{-\rho_{im}^{c}}]^{-1/\rho_{im}^{c}}$$

$$M_{im} = D_{im}\,[(PM_{im}/PD_{im})((1-\alpha_{im}^{c})/\alpha_{im}^{c})]^{-\sigma_{im}^{c}}$$

$$X_{ie} = \beta_{ie}^{t}[\alpha_{ie}^{t}\,E_{ie}^{\rho_{ie}^{t}} + (1-\alpha_{ie}^{t})\,D_{ie}^{\rho_{ie}^{t}}]^{1/\rho_{ie}^{t}}$$

$$E_{ie} = D_{ie}\,[(PE_{ie}/PD_{ie})((1-\alpha_{ie}^{t})/\alpha_{ie}^{t})]^{\sigma_{ie}^{t}}$$

$$Q_{imn} = D_{imn}$$

$$X_{ien} = D_{ien}$$

A.1.4. Income and expenditure block

$$YF^{lab} = \sum_i W_i LD_i$$

$$YF^{cap} = \sum_i R_i KD_i - DEP$$

$$DEP = \sum_i \tau_i^{dep} PK_i KD_i$$

$$YH = YF^{lab} + YF^{cap} - \alpha^{fg}\,YF^{cap} - \alpha^{fr}\,YF^{cap} + TR^{gh} + TR^{fh}$$

$$YG^{t} = \sum_i(\tau_i^{idt}PX_iX_i - \tau_i^{sb}PX_iX_i + \tau_i^{mt}PM_i^{w}ERM_i)$$

$$YG = YG^{t} + \tau^{dt}YH + \alpha^{fg}YF^{cap} + TR^{fg}$$

$$YD = YH - \tau^{dt}YH$$

$$SAVH = mpsYD$$

$$SAVG = gsr(YG - \tau^{tgh}YG)$$

$$GC_iPQ_i = \gamma_i^{g}(YG - \tau^{tgh}YG - SAVG)$$

$$HC_iPQ_i = \gamma_i^{h}(YD - SAVH)$$

$$SAVT = DEP + SAVH + SAVG + SAVF$$

$$\sum_i PM_i^{w}\,M_iER + TR^{hf} + \alpha^{fr}YF^{cap} = \sum_i PE_i^{w}\,E_iER + TR^{fh} + TR^{fg} + SAVF$$

$$GDPN = \sum_i(W_iLD_i + R_iKD_i + \tau_i^{idt}PX_iX_i - \tau_i^{sb}PX_iX_i + \tau_i^{mt}PM_i^{w}ERM_i)$$

$$GDPR = \sum_i(HC_i + GC_i + FI_i + SI_i + PE_{ie}^{w}E_i - PM_i^{w}M_i)$$

A.1.5. Investment block

$$SI_i = \gamma_i^{s}X_i$$

$$KE = INV - \sum_i(SI_i\,PQ_i)$$

$$FI_i = \gamma_i^{f}KE/PK_i$$

A.1.6. Equilibrium block

$$Q_i = \sum_j MI_{i,j} + HC_i + GC_i + FI_i + SI_i$$

$$\sum_i LD_i = LS$$

$$SI^{bal} = SAVT - INV$$

A.1.7. Environmental block

$$EM_{s,p,i} = MI_{s,i}\,\eta_s\,\varpi_{s,p,i}\,\chi_{s,i}$$

$$T_{CO_2} = \sum_{s,i} P_{CO_2}\,EM_{s,CO_2,i}$$

$$CP_{s,i} = P_{CO_2}\,\eta_s\,\varpi_{s,CO_2,i}\,\chi_{s,i}$$

A.2. Indices

i,j	production sectors
im	sectors with imports
imn	sectors without imports
ie	sectors with exports
ien	sectors without exports
ine	non-energy sectors
s	fossil energy sectors
p	pollutants

A.3. Parameters

β_i^{vae}, β_i^{va}, β_i^{en}, β_i^{f}, β_i^{ns}	scale parameters in CES production function
α_i^{vae}, α_i^{va}, α_i^{en}, α_i^{f}, α_i^{ns}	share parameters in CES production function
σ_i^{vae}, σ_i^{va}, σ_i^{en}, σ_i^{f}, σ_i^{ns}	elasticity of substitution in CES production function

ρ_i^{vae}, ρ_i^{va}, ρ_i^{en}, ρ_i^{f}, ρ_i^{ns} exponent parameters in CES production function
$\beta_i^c(\alpha_i^c)$ Armington function scale (share) parameter
$\rho_i^c(\sigma_i^c)$ Armington function exponent (elasticity) parameter
$\beta_i^t(\alpha_i^t)$ CET function scale (share) parameter
$\rho_i^t(\sigma_i^t)$ CET function exponent (elasticity) parameter
$e_i^{el}(e_i^{fX})$ electricity (fossil energy) efficiency growth parameter
e_i^k capital technological growth parameter
e_i^l labor efficiency growth parameter
$ivae_i$ capital–labor–energy composite share parameter
imc_i non-energy intermediate composite share parameter
$im_{ine,j}$ non-energy intermediate inputs coefficient matrix
τ_i^{mt} import tax (tariff) rates
τ_i^{idt} indirect tax rates
τ_i^{sb} production subsidy rates
τ_i^{dep} capital wear & tear (depreciation) rates
τ^{dt} direct tax rate
τ^{tgh} government to household transfer rate
α^{fg} government factor income share
α^{fr} foreign factor income share
mps household marginal rate to save
gsr government saving rate
γ_i^s stock investment share by sector
γ_i^g government consumption share by sector
γ_i^h household consumption share by sector
γ_i^f fixed capital investment share by sector
η_s energy conversion coefficients
$\varpi_{s,p,i}$ pollutant emission conversion coefficients
$\chi_{s,i}$ share of fuel related use of fossil energy

A.4. Exogenous variables

PM_{im}^w world import price of imported goods
PE_{ie}^w world export price of exported goods
$SAVF$ foreign savings (current account deficit)
LS supply of labor force
TR^{fh} foreign transfers to household
TR^{fg} (net) foreign transfers to government
P_{CO_2} CO_2 price ($/ton)
$CP_{s,i}$ pollutant cost of fossil energy inputs

A.5. Endogenous variables

X_i domestic sectoral output (gross of tax)
$INTC_i$ non-energy intermediate input composite
$INT_{ine,j}$ non-energy intermediate input demand matrix
$GDPN$ nominal gross domestic product
$GDPR$ real gross domestic product
VAE_i capital–labor–energy (KLE) composite
VA_i value added (capital, labor) composite
KD_i fixed capital demand by sector
LD_i labor force demand by sector
EN_i energy (fossil energy, electricity) composite
FE_i fossil energy composite
EL_i electricity demand by sector
NSF_i non-solid fossil energy composite
$COAL_i$ coal demand by sector
OIL_i oil demand by sector
GAS_i gas demand by sector
DEF GDP deflator
Q_i Armington composite good
M_i imports from RoW by sector
E_i exports from RoW by sector
D_i domestic production used domestically
PM_i local price of imported goods
PE_i local price of exported goods
PQ_i price of composite goods
PD_i price of domestic goods
PX_i price of domestically produced goods
$PVAE_i$ capital–labor–energy composite price
PVA_i capital–labor composite price
PEN_i energy aggregate (fossil energy, electricity) price
PFE_i fossil energy aggregate price
PEL electricity input price
$PNSF_i$ non-solid fossil energy aggregate price
$PS_{s,i}$ fossil energy input price
PK_i capital goods price
W_i labor wage rates
R_i gross capital rental rates
ER exchange rate
YF^{lab} total factor income for labor
YF^{cap} total net factor income for capital
DEP fixed capital depreciation (wear & tear)
YH total household income
YD household disposable income
YG^t government indirect tax (net) and tariff revenue
YG total general government revenue
$SAVH$ net household (private) savings
$SAVG$ government savings
$SAVF$ foreign savings (current account deficit)
$SAVT$ total gross savings
HC_i household consumption by sector
GC_i government consumption by sector
$MI_{i,j}$ intermediate inputs (energy, non-energy) demand matrix
INV total investment income
SI_i inventory investment
KE fixed capital investment income
FI_i total market fixed capital investment
SI^{bal} saving–investment balance (Walrasian market clearing)
$EM_{s,p,i}$ pollutant emissions by sector, type and source
T_{CO_2} total pollutant tax revenues

Table B1
Elasticity values used in the model.
Sources: Bohringer and Rutherford (1997), Naqvi (1998), Timilsina and Shrestha (2006), Fæhn et al. (2009), Labandeira et al. (2009), Wang et al. (2009), He et al. (2010), and Debowicz et al. (2012b).

Sectors	$\sigma^{(kl)e}$	σ^{kl}	σ^{en}	σ^{f}	σ^{ns}	σ^{c}	σ^{t}
Agriculture	0.5	0.68	0.6	0.5	2.0	2.47	3.9
Crude oil and natural gas	0.4	0.6	0.5	0.5	2.0	3	–
Other minerals	0.3	0.6	0.6	0.5	2.0	2.47	2.9
Food and beverages	0.5	0.6	0.6	0.5	2.0	3.2	3
Textile and Wearing apparel	0.5	0.6	0.6	0.5	2.0	3.2	4.6
Paper, wood and furniture	0.5	0.6	0.5	0.5	2.0	3.2	3
Chemical products	0.3	0.6	0.25	0.5	2.0	0.5	2.9
Basic Metal products	0.3	0.5	0.25	0.5	2.0	2.8	2.9
Fabricated metal products	0.7	0.5	0.2	0.5	2.0	3.2	2.9
Non-metallic mineral products	0.3	0.5	0.25	0.5	2.0	3.2	2.9
Electrical machinery	0.5	0.5	0.2	0.5	2.0	2	2.9
Non-electrical machinery	0.5	0.5	0.2	0.5	2.0	2.8	2.9
Other manufacturing products	0.7	0.5	0.6	0.5	2.0	2.59	2.9
Coal Products	0.3	0.8	0.5	0.5	2.0	3	–
Petroleum products	0.3	0.5	0.25	0.5	2.0	0.8	2.0
Gas supply	0.4	0.5	0.1	0.5	2.0	–	–
Electricity	0.3	0.5	0.1	0.5	2.0	–	–
Construction	0.7	0.95	0.2	0.5	2.0	–	–
Transport services	0.5	0.6	0.25	0.5	2.0	–	2
Other services	0.7	0.9	0.25	0.5	2.0	1.91	2

Appendix B

See Table B1.

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