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CO_2, GDP and RET: An aggregate economic equilibrium analysis for Turkey

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ABSTRACT

There is a worldwide interest in renewable electricity technologies (RETs) due to growing concerns about global warming and climate change. As an EU candidate country whose energy demand increases exponentially, Turkey inevitably shares this common interest on RET. This study, using an aggregate economic equilibrium model, explores the economic costs of different policy measures to mitigate CO_2 emissions in Turkey. The model combines energy demands, capital requirements and labor inputs at a constant elasticity of substitution under an economy-wide nested production function. Growing energy demand, triggered by economic growth, is met by increased supply and initiates new capacity additions. Investment into RET is encouraged via the incorporation of (a) endogenous technological learning through which the RET cost declines as a function of cumulative capacity, and (b) a willingness to pay (WTP) function which imposes the WTP of consumers as a lower bound on RET installation. The WTP equation is obtained as a function of consumer income categories, based on data gathered from a pilot survey in which the contingent valuation methodology was employed. The impacts of various emission reduction scenarios on GDP growth and RET diffusion are explored. As expected, RET penetration is accelerated under faster technological learning and higher WTP conditions. It is found that stabilizing CO_2 emissions to year 2005 levels causes economic losses amounting to 17% and 23% of GDP in the years 2020 and 2030, respectively.

1. Introduction

As an EU candidate country, with which accession negotiations have started (in October 2005), Turkey shall adopt the community acquis. Under energy and environment chapters, the country's related legislation is currently being scrutinized within a detailed screening process. New and renewable sources of energy form an agenda item under the energy chapter. The Kyoto Protocol forms an agenda item under the environment chapter. The two agenda items in separate chapters are closely related as new and renewable forms of energy will contribute to greenhouse gas emission reduction. Turkey's renewable energy sources shall therefore become a focus of interest during the accession talks under both chapters. Economically feasible renewable power generation potentials have been estimated at 196.7 TWh/a for biomass energy, 124 TWh/a for hydropower, 102.3 TWh/a for solar energy, 50 TWh/a for wind power and 22.4 TWh/a for geothermal energy (Evrendilek and Ertekin, 2003). In electricity generation, renewables accounted for 30.7% (46.34 TWh) in 2004, of which hydroelectric energy was absolutely dominating (99.5%).

Official energy supply mix projections do not forecast a rapid expansion of new renewable electricity technologies (RETs), which can be explained by relatively high investment costs as compared to traditional fossil fuel-based technologies. Reducing greenhouse gas emissions at a low cost without harming economic growth appears to be a challenge for Turkey. Given this challenge for sustainable development, Turkey emerges as an interesting case study to explore energy–economy–environment interactions with particular focus on the diffusion prospects for new RETs. The adoption of new RETs is naturally subject to developments that bring down unit generation costs to a level where these technologies can actually compete with conventional ones. This might happen with increased exposure to RET due to experience accumulation, which typically improves the technical and economical performance, productivity and organizational efficiency. The learning effect, also referred to as 'technological learning', is indeed an empirical artifact as many applications have shown (e.g. Arrow, 1962; BCG, 1970; Lieberman, 1987; Argot and Epple, 1990; Barreto, 2001).

Intimate relationships between RET/non-RET energy prices and demand levels, pollutant emissions and economic growth necessitate an integrated framework for energy policy and planning.

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The literature covers various modeling techniques for numerical policy analysis, ranging from linear programming to mixed complementarity programming. There is a great variety of approaches and methodologies used in energy and environmental policy modeling. However, even though the approaches are quite different with respect to the structure and focus of models, there is a common core that inherits some optimization methodology.

There are two broad classes of models describing the relationships between the energy sector and the rest of the economy: top-down and bottom-up. The first category approaches the problem from a macro-economic perspective with an aggregate energy sector representation, whereas the second one adopts a technology-rich description of energy activities including cost structures, conversion efficiencies and technological limitations from primary to final energy. The top-down label derives from how modelers apply economic theory and techniques to historical data on consumption, prices, incomes and factor costs to model supply and final demand. Therefore, top-down models evaluate the system from an economic viewpoint, in contrast to bottom-up models which consider energy systems and conversions in detail from an engineering viewpoint.

In this study, a top-down policy analysis model computing an aggregate economic equilibrium (AEE) is developed and calibrated for Turkey. Accounting of the consumer willingness to pay (WTP) for CO_2 emission reduction and endogenized technological learning for new RETs are two particular strengths of the model. The impacts of various energy and environmental policy scenarios on CO_2 emissions, GDP growth and RET diffusion are explored. GDP losses are interpreted as the economic costs of emission reductions. Yet the corresponding benefits are considered to be beyond the scope of this study.

The theoretical background of the model is discussed in the next section introducing the AEE approach, the methodology for determining WTP and the theory of technological learning. Section 3 provides the model description. The empirical analysis and model results are presented in Section 4. Finally, Section 5 concludes the study.

2. Literature survey

2.1. The aggregate economic equilibrium approach

AEE models are classified under the top-down approach. They describe investment and consumption patterns, and emphasize short-run energy and environmental policy dynamics. Final demand determines the size of the economy, and the models work to balance quantity based on exogenous prices. Capital stock turnover and new technology penetration rates can be explicitly and endogenously formulated under this approach. However, the economy representation is aggregate. Typically, there is an economy-wide production function, generally in CES-form, relating capital (K), labor (L), energy (E) and other inputs (O) to produce gross output (Y), i.e. $Y = f(K, L, E, O)$. Gross output is further computed as the sum of energy costs (EC) and GDP, i.e. $Y = EC+GDP$. The addition of EC to GDP involves deliberate double counting (as GDP accounting typically already includes the cost of energy) in order to feature an accounting of energy–economy interactions. However, the effect of double counting is in a way penalized by the inclusion of energy as an explicit factor of production. That is, energy is treated as an intermediate good only (e.g. there is demand for transportation rather than gasoline) contributing to the ultimate production of final goods and services. Hence, energy costs enter only indirectly into gross production. Although this approach is not fully satisfactory from an economic point of view, it provides a fairly well representation of the two-way linkage between the energy sector and the rest of the economy. The production function parameters are determined from optimality conditions to maximize the profit of producers for a representative year. Consumer utility maximization, on the other hand, is envisaged in the overall objective function. That is how both parties are taken care of so that the model yields an AEE. The AEE accounting conventions are derived in Hogan and Manne (1979) where the theory is introduced under the metaphor of the fable of the elephant (the economy) and the rabbit (the energy sector).

The literature covers various macroeconomic models using the AEE approach for energy and environmental policy modeling. These include MERGE (Manne et al., 1995), CETA (Peck and Teisberg, 1992), MARKAL-MACRO (Manne and Wene, 1992), NEMS (Hoffman and Stephan, 1996), MEEET (Arıkan and Kumbaroğlu, 2001), GLOBAL 2100 (Manne and Richels, 1994), MIS (Kuckshinrichs and Kemfert, 1997), RICE (Nordhaus and Yang, 1996) and GRAPE (Kurosawa et al., 1999), among others. These models are widely used to reflect the economic effects of greenhouse gas emission reduction policies in a medium to long planning horizon. One of them, namely MERGE, considers the consumers' WTP for CO_2 emission reduction, which is also a major feature of our model. MERGE assumes an S-shaped curve for the relationship between WTP and per capita income. A theoretical WTP value is computed as a function of per capita income and temperature change, calibrated such that the WTP does not exceed 100% of GDP. However, there is lack of empirical evidence and a great deal of uncertainty involved that may induce misleading policy implications if consumer WTP is not truly represented.

2.2. Willingness to pay for CO_2 emission reduction

A central problem for an economic analysis with non-marketed goods (i.e. goods that are not sold or bought in the market) such as CO_2 emissions is the difficulty of placing a monetary value on them. WTP offers an approximation to this value. It is defined as the maximum amount of money an individual might want to pay to equalize a utility change. The maximum amount an individual is willing to pay is assumed to be an indicator of the value he/she places on the good or service. For direct measurement of WTP, the contingent valuation methodology (CVM) emerges as a generally favored survey technique that is widely used by economists to value non-marketed assets (Brookshire and Eubanks, 1978; Schulze and D'Arge, 1978). In this approach, individuals are directly asked the amount they would be willing to pay for a non-marketed good through survey questions (Mitchell and Carson, 1989; Bjornstad and Kahn, 1996; Bateman and Willis, 1999). Respondents display their feelings or choices in terms of WTP for the non-marketed good. To increase the possibility of valid and reliable answers, a typical CVM study starts by making the respondent familiar about the environmental good to be valued. Information on the proposed changes, implications and the financing procedures are clearly explained in a hypothetical scenario.

The questioning approaches employed in a CVM survey are basically fourfold:

- *Open-ended:* Respondents are directly asked the maximum amount they would be willing to pay for a specified change in the good to be valued.
- *Dichotomous choice:* The questioning is arranged in two parts. The first one investigates whether the respondents are willing to pay for a specified change in an environmental asset. If willingness exists, then a second question asks whether the WTP is equal to a specified amount.

- *Bidding games:* Respondents are asked whether they are willing to pay a specified amount of money. If the answer is 'Yes', then the question is repeated asking for a higher value. This process continues until a 'No' response is obtained.
- *Payment card:* Respondents are shown a card having a range of payment alternatives. Then, they are expected to identify their preferences on the card.

Questions related to WTP are followed by a series of socio-economic and demographic questions. In this way, it becomes possible to investigate the relationship between WTP and demographic/socioeconomic information.

Possible biases related to the scope and results of the CVM are discussed by Diamond and Hausman (1994), Boyle et al. (1994), Cummings et al. (1994, 1995), Willis and Garrod (1991), among others.

2.3. Learning curves and RET adoption

Learning curves, sometimes also synonymously referred to as 'progress curves' or 'experience curves', are used to empirically quantify future cost reductions based on an extrapolation of historical trends. They estimate the development of marginal or average unitary cost as a function of cumulative production or capacity. Experience and know-how accumulation by the labor force and management, technical progress due to repetitive production and improvements in the production process and/or organizational efficiency can be considered as the major sources for reduction in cost due to the learning effect. The concept has gained empirical support in many applications (e.g. Neij, 1997, 1999a, b; IEA, 2000; Ibenholt, 2002; Junginger et al., 2005; Kamp et al., 2004).

'Learning rates' express the rate at which estimated unit cost decreases for each doubling of cumulative production or capacity (both of which can be used to approximate the accumulation of experience/know-how when the technology is installed). Its complement, the 'progress ratio', defines the corresponding percentage change in cost. The common formulation of the learning curve is

$$Cost = Cost_0 Cum^{li}$$

where *Cost* is the per unit investment cost of the technology at a cumulative capacity (or production) level of *Cum*, $Cost_0$ is the cost at capacity level *Cum* and *li* is a learning (experience) index relating to the decline in cost. The percentage change in cost can easily be computed for each doubling of cumulative capacity Cum as $1-2^{li}$, which is referred to as the learning rate (implying a progress ratio of 2^{li}).

In this study we make use of learning curves for new RETs in order to take into consideration that these technologies might be able to successfully compete with conventional technologies at some time in the future due to cost reductions based on experience accumulation. This allows us to model the prospects for renewable energy technology adoption and diffusion in the light of declining unit costs, which can provide useful insights into policy-makers on how to promote RET diffusion or to steer towards a desired technological composition of the energy sector.

2.4. Other empirical studies

Various recent studies examine the effect of CO_2 emission stabilization on GDP in different regions of the world. There is, however, only one study carried out for the case of Turkey to our knowledge. Telli et al. (2008) investigate the economic effects of emission scenarios in a computable general equilibrium model for Turkey for the period 2005–2020. They apply three different quota levels: 90% quota (reducing emission by 10% of the base-run, 2003), 80% quota and 60% quota on CO_2 emissions. The results show that imposition of CO_2 quota at 90% level reduces the rate of growth of GDP and leads to a 7.1% fall in GDP compared to base-run scenario results in 2020. Furthermore, if the quota is set at 60% level, there is a 36.8% reduction in the GDP of year 2020. The approach and structure of the model, its parameters, and basic assumptions are different than ours. Therefore the paper's findings do not allow for direct comparison.

Masui (2005) used AIM/Material, a CGE model of the Japanese economy, to investigate the economic costs of CO_2 reduction. 1995 is used as the base year and the model is calculated year by year until 2010. Environmental constraints on CO_2 emissions, based on the Kyoto Target of UNFCCC, and final disposal of solid wastes define an environmental scenario, which leads to an economic loss amounting to 0.2% of GDP in 2010.

Chen et al. (2007) studied China energy system's carbon mitigation strategies and corresponding impacts on the economy by using the MARKAL family models, using dynamic linear programming to minimize the total discounted energy system cost. Their study analyzes the GDP loss in the whole planning period for the emission constraints set from 2020. Results show that the absolute GDP loss increases gradually in the planning horizon (1995–2050) and reaches the highest by 2050 for all nine different emission reduction scenarios. The China MARKAL modeling shows that the marginal abatement cost in 2020 for the reduction rate of 45% from 2020 onwards is 311 US$/tC, but it would drop by 39%, 64% and 67% if China MARKAL-MACRO, China MARKAL-ED and China MARKAL-EDI are applied, respectively. This divergence of findings under the same family of models and under same assumptions highlight the uncertainty inherent in the results, and the importance of the approach employed.

3. Model formulation

An energy–economy–environment integrated policy analysis model, which is developed to study economically sustainable energy and environmental policies for Turkey, is presented in this section.

The model aggregates energy submodels of demands, capital requirements and labor inputs under an economy-wide nested CES production function. Growing energy demand is met by increased supply produced by various alternatives including a variety of RETs. The associated environmental submodel includes feedback links both to the energy sector and economy as defined by the WTP of customers. Fig. 1 provides an illustration of interactions between the three main modules (energy, economy and environment) of the model.

The submodels are linked to obtain equilibrium solutions through utility maximization over a planning horizon of *T* periods. In consistence with the conventional theory of consumption, utility (U) is defined as the totality of the discounted logarithm of consumption (C_t). Hence, the objective function is formulated as

$$\max U = \sum_{t=1}^{T} \Delta_t \log C_t \tag{1}$$

where Δ_t is the utility discount factor. Each individual time period identifies a representative year *t*.

3.1. The economy submodel

The conventional macroeconomic identity defines GDP as

$$GDP_t = C_t + I_t + X_t - M_t \tag{2}$$

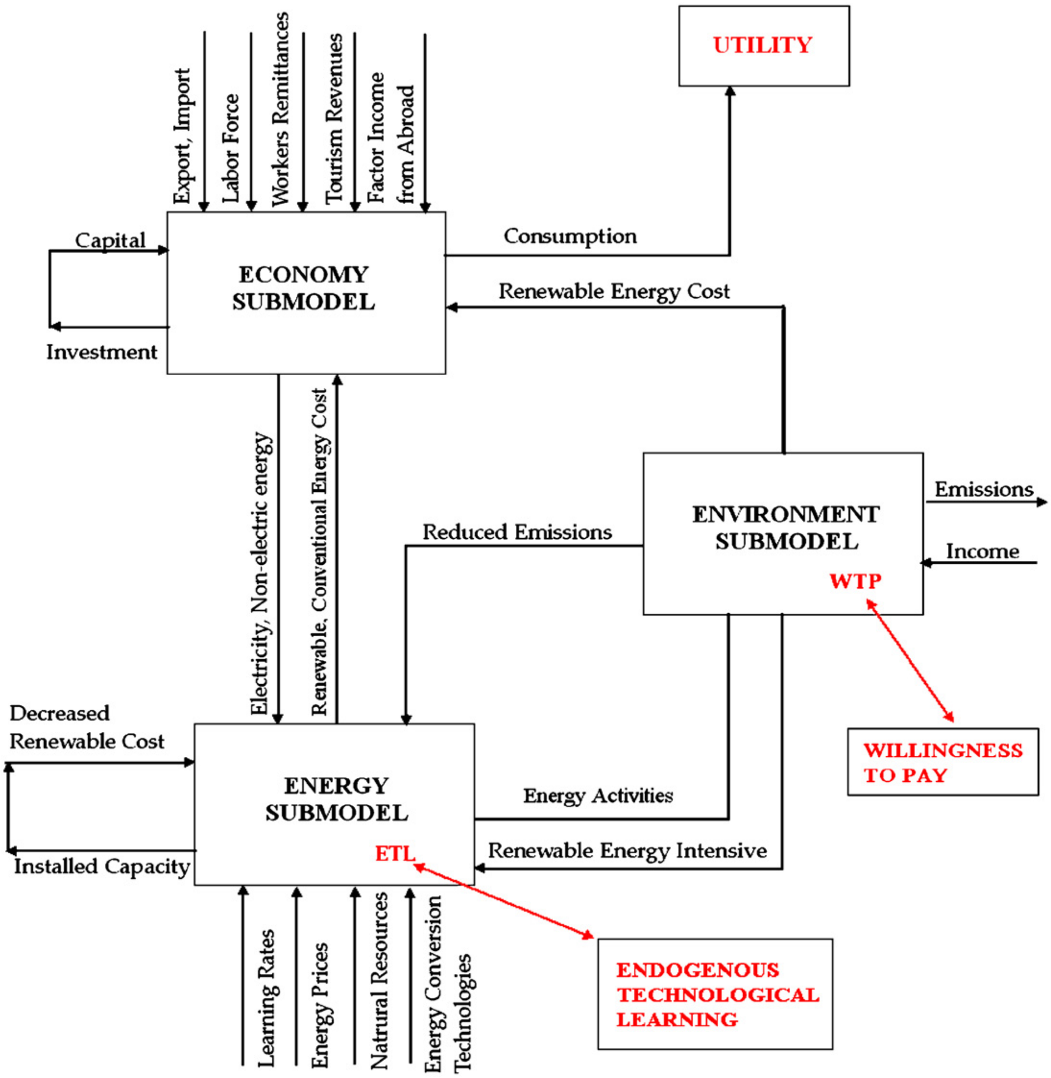

Fig. 1. Illustration of model interactions.

where I_t, X_t and M_t represent investments, exports and imports, respectively. The relation between GDP and gross production (Y_t) is established as

$$Y_t = GDP_t + EC_t \tag{3}$$

which is typical for the AEE approach as explained in Section 2.1.

Production is described within a nested structure of an economy-wide neoclassical production function aggregating energy service demands (E_t, NE_t) and primary factors (K_t, L_t) at a constant elasticity of substitution (the elasticity of substitution between the primary and energy aggregate pairs being constantly ($\sigma = 1/1-\rho$)). Energy comes up from the aggregation of electricity (E_t) and non-electric energy (NE_t) at a unitary elasticity of substitution (Cobb–Douglas). Capital (K_t) and labor (L_t) are combined in Cobb–Douglas form to yield the primary aggregates. A putty-clay representation is adapted in the production function, i.e. substitution is allowed only among newly added variables, whereas the remaining stocks remain unchanged. The incremental production (YN_t) in period t is

$$YN_t = \gamma_t \left[\alpha_t [KN_t^{sk} LN_t^{sl}]^\rho + \beta_t [EN_t^{se} NEN_t^{sne}]^\rho\right]^{1/\rho} \tag{4}$$

where γ_t, α_t, β_t are scale parameters. The letter N, added to the end of all variables, indicates incremental values *Newly* added to existing stocks. The parameters *sl*, *sk*, *se* and *sne* stand for the value shares of labor, capital, electricity and non-electric energy, respectively.

Total production (Y_t) for period t is calculated from the addition of new production to the stock surviving from the previous period, i.e.

$$Y_t = YN_t + \lambda^p Y_{t-1} \tag{5}$$

where p is the number of years between two successive time periods. The constant λ is the annual survival factor which reflects the rate of decline in existing stocks due to retirement. The same relations are also established for the surviving stocks of K_t, E_t and NE_t:

$$K_t = KN_t + \lambda^p K_{t-1} \tag{6}$$

$$E_t = EN_t + \lambda^p E_{t-1} \tag{7}$$

$$NE_t = NEN_t + \lambda^p NE_{t-1} \tag{8}$$

Increments in capital during a p-year period are defined as the average of previous and current period investments:

$$KN_t = 1/2p(I_t + I_{t-1}) \tag{9}$$

A foreign trade constraint restricts imports so as not to exceed the sum of exports (X_t), imports (M_t), factor incomes from abroad (F_t), worker remittances (W_t) and tourism revenues (TR_t):

$$M_t \leqslant X_t + F_t + W_t + TR_t \tag{10}$$

By setting upper and lower bounds for import and export as a fraction of GDP, foreign trade values are restricted to overcome possible distortion due to market imperfection and follow the optimal time path anticipated by utility maximization:

$$X_t \geqslant \eta_1\, GDP_t \tag{11}$$

$$M_t \leqslant \eta_2\, GDP_t \tag{12}$$

Energy demand and cost relationships establish the link between the energy and economy submodels. Energy costs are composed of conventional energy cost (CEC_t) and renewable energy cost (REC_t):

$$EC_t = CEC_t + REC_t \tag{13}$$

These two main cost components are defined in the energy submodel as described in the following.

3.2. The energy submodel

The energy submodel differentiates primarily between two groups of energy consumption: electricity (E_t) and non-electric energy (NE_t):

$$E_t = \sum_k ELEC_{t,k} \tag{14}$$

$$NE_t = \sum_m NELEC_{t,m} \tag{15}$$

$ELEC_{t,k}$ and $NELEC_{t,m}$ represent the energy coming from technology type k and fuel type m used for generating electricity and non-electric energy, respectively.

The replacement of energy technologies occurs at the end of a useful lifetime of 30 years, as defined by the following depreciation equations:

$$ELEC_{t+1,k} = ELEC_{t,k} + p\, ELECINC_{t+1,k} - p/30\, ELEC_{t=0,k} \tag{16}$$

$$NELEC_{t+1,m} = NELEC_{t,m} + p\, NELECINC_{t+1,m} - p/30\, NELEC_{t=0,m}$$
$$\text{for } t \leqslant 30/p \text{ and} \tag{17}$$

$$ELEC_{t+1,k} = ELEC_{t,k} + p\, ELECINC_{t+1,k} - p\, ELECINC_{t-(30/p),k} \tag{18}$$

$$NELEC_{t+1,m} = NELEC_{t,m} + p\, NELECINC_{t+1,m} - p\, NELECINC_{t-(30/p),m}$$
$$\text{for } t > 30/p \text{ and} \tag{19}$$

where $ELECINC_{t,k}$ and $NELECINC_{t,m}$ define incremental levels for electric and non-electric energy technologies, respectively, and p denotes the period length in years.

A main technological distinction is made to differentiate between the cost of conventional and renewable power generation. Conventional energy cost (CEC_t) is computed as the totality of the cost coming from the fossil fuel-based technologies, while renewable electricity cost (REC_t) is obviously the sum of the cost of different renewable power generation technologies:

$$CEC_t = \sum_k ELEC_{t,k}\, c^e_{t,k} + \sum_k NELEC_{t,m}\, c^{ne}_{t,m} \tag{20}$$

$$REC_t = \sum_k ELEC_{t,k=ren}\, c^r_{t,k=ren} \tag{21}$$

where $c^e_{t,k}$ and $c^{ne}_{t,m}$ represent the per unit generation costs for electric and non-electric energy, respectively. The cost for renewable power generation, $c^r_{t,k=ren}$, is a function of installed capacity (featuring technological learning for RETs):

$$c^r_{t,k=ren} = c^r_{t=0,k=ren}\, CUM^{li_k}_{t,k=ren} \tag{22}$$

where $c^r_{t,k=ren}$ is the cost for each type of renewable electricity in time period t. $CUM_{t,k}$ and li_k represent the cumulative production and learning index for each type of renewable energy, respectively. In this manner, RET costs are reduced for each doubling of cumulative installed capacity by the learning rate ($1–2^{li_k}$). The cumulative production is computed from the ratio of current to initial production level:

$$CUM_{t,k} = ELEC_{t,k=ren}/ELEC_{t=0,k=ren} \tag{23}$$

The cost of RETs is related to a WTP function which defines the willingness of consumers to pay an additional cost for the reduction in CO_2 emissions via an increased use of RET-based electricity. The WTP equation is defined in the following section under the environmental submodel.

3.3. The environmental submodel

A WTP function for CO_2 emission reduction is derived on the basis of data gathered from a survey. The function, emerging from a linear regression analysis of survey results, assigns a WTP value for a representative household. In order to obtain a nationwide WTP value, the regression equation is multiplied by the total number of households (HN_t):

$$WTP_t = HN_t \left(a + \sum_i b_i\, IClass_{t,z} \right) \tag{24}$$

where $IClass_{t,z}$ represents the percentages of the households entering income class z in period t; the parameters a and b_i are the regression coefficients.

The household number dynamics is established as

$$HN_{t+1} = HN_t(1+\omega)^p \tag{25}$$

where ω symbolizes the annual household growth rate. Average monthly incomes of the households are disaggregated into sequential classes as defined by the regression equation (see Eq. 28).

The WTP value is used as a lower bound on the cost of RETs, ensuring that new RET installations are at least as high as the consumers' WTP:

$$REC_t \geqslant WTP_t \tag{26}$$

Finally, the CO_2 emissions are computed by applying the emission factors (ef^{elec}_k, ef^{nelec}_m):

$$CO2_t = \sum_k ELEC_{t,k}\, ef^{elec}_k + \sum_m NELEC_{t,m}\, ef^{nelec}_m \tag{27}$$

This concludes our model formulation. In the following, we present an application using data from Turkey.

4. Empirical analysis and model results

4.1. A CVM survey application

A WTP function is derived on the basis of data gathered from a pilot survey conducted on a randomly selected set of 101 individuals. The CVM is employed as a generally favored survey technique for assigning monetary values on non-marketed assets.

The questionnaire is organized in five sections. The first part includes a half-page introductory informative text describing CO_2

emissions and the purpose of the survey. The emission context is introduced as follows:

The residential sector contributes to 38% of national CO_2 emissions, which originate from the fossil fuel consumption used for cooking, space and water heating, as well as from the fossil fuel consumption used for generating the electricity that is demanded by the households. Findings of a Turkish study on CO_2 Emissions (Kumbaroğlu et al., 2008) shows that a 1% reduction in CO_2 emissions will provide the same environmental benefit as not driving a car a total of 426 km.

The second section provides warm-up questions which make respondents familiar to the impact of fossil fuel use on CO_2 emissions. Five-point Likert-scale[1] questions are applied aiming to increase the knowledge of respondents. The third section begins with background information to make respondents think carefully about their responses. It then continues with the related contingent valuation scenario. The WTP questions located at the end of the scenario are developed as a combination of dichotomous choice and bidding game formats. The scenario defines CO_2 payment as a mandatory surcharge on electricity consumption, which is collected by public institutions and managed by the Scientific and Technical Research Council to establish fund for the subsidization of environmentally friendly technologies. First, two different scenarios requiring two different payment levels are arranged with respect to the scenario definition above: 5% and 10% of electricity bills. Respondents not willing to pay that much are asked if they would be willing to pay less: 1% and 5%, depending on the scenario. Respondents accepting the first payment level, on the other hand, are asked if they would be willing to pay a higher amount: 10% and 15%, depending on the scenario. This is repeated several times until the highest amount that a respondent is willing to pay is identified. Finally, questions in the last section try to determine the environmental consciousness and attitudes of respondents using again a five-point Likert-scale questioning. The final section then examines demographic and socioeconomic data of participants, such as age, gender, education and income class.

Socioeconomic and demographic variables are determined as possible explanatory variables to be included in the WTP function. Hence, income class distribution, age, education and gender are also investigated to support the understanding of why individuals are willing to pay or why they are not, and with the possibility to include the explanatory variables in the WTP function upon evaluation of the responses.

Systematic differences among the responses are evaluated using the linear regression analysis. A respondent's income class, age and education level are considered as independent variables that can affect his/her WTP. The method of ordinary least squares is applied to estimate the regression coefficients.

The highest explanatory power (yielding an R-square value of 0.61) is obtained when age, education and income class are all included in the model as categorical independent variables. However, according to both t-test and ANOVA results, age and education are determined as insignificant terms of the model, and thus eliminated from the analysis. Hence, WTP is displayed as a function of income class only (with an R-square of 0.5718). The t-test, confidence intervals on the individual regression coefficients, ANOVA results, normality and independence checks are given in Appendix A.4. The final WTP equation obtained is as follows:

$$WTP_t = HN_t(7262 - 5575IClass_{1,t} - 5243IClass_{3,t} - 4708IClass_{3,t} - 5527IClass_{4,t} - 4329IClass_{5,t} \quad (28)$$

[1] Likert scale is a questioning method that asks respondents to indicate their degree of agreement or disagreement with a statement, measured on a scale which typically varies from 1 to 5, e.g., 1 = strongly disagree, 2 = disagree, 3 = not sure, 4 = agree and 5 = strongly agree.

4.2. Model calibration and BAU results

The model is calibrated for a business-as-usual (BAU) reference scenario with year 2000 being the base year (there were no extra ordinary political, social or economic events that could affect energy consumption habits or economic balances in year 2000) and solved in 5-year time steps. Results for the first period are compared with actual realizations, validating the model at a tolerance level of $\pm 1\%$. Base year macroeconomic and energy data values are shown in Tables 1 and 2.

BAU assumptions on model parameters are shown in Table 3.

The production function parameters are determined through optimality conditions. Their derivations can be found in Karali (2006).

The programming environment General Algebraic Modeling System has been used as the formulation outlet and the solver Modular In-core Nonlinear Optimization System, which relies on a reduced gradient algorithm, has been utilized to obtain model results. Results are obtained until 2050, but only those until 2035 are reported in order to eliminate end-of-horizon distortions.

Fig. 2 illustrates annual BAU growth rates of the main economic indicators. The high growth rates in the first period represent an economic boom after major financial crises that occurred in 2000–2001. In the long run GDP growth stabilizes at about 5% p.a, which is consistent with the realized growth data obtained from State Planning Organization (SPO). SPO data display an annual growth of almost 5% between years 2000 and 2005 and 4% between years 1996 and 2005.

Main indicators of energy use are presented in Table 4. Total electricity consumption rises around 6.2% annually in the first decade and increases thereafter at an average rate of about 4% until the end of the planning horizon. Total share of natural gas and hydroelectricity in electricity generation is significantly large in the long run. Wind power is the most preferred renewable energy

Table 1
Macroeconomic data for the base year (2000)

Macroeconomic data	Value (10^9 \$)
GDP	205.07$^{(1)}$
Consumption	95.88$^{(2)}$
Import	27.78$^{(2)}$
Export	54.50$^{(2)}$
Investment	135.92$^{(1)}$
Factor incomes from abroad	0.98$^{(1)}$
Workers' remittances	4.56$^{(1)}$
Tourism revenues	7.64$^{(1)}$

Data Sources: (1) SPO, 2005; (2) TSI, 2005.

Table 2
Energy data for the base year (2000)

Source	Electric energy		Non-electric energy	
	(TWh)	(cent/kwh)	(Mtoe)	(\$/ton)
Oil	7.18$^{(1)}$	4.22$^{(1)}$	8.21$^{(1)}$	164.93$^{(1)}$
Hard coal	3.60$^{(1)}$	4.55$^{(1)}$	29.83$^{(1)}$	100.52$^{(1)}$
Lignite	35.63$^{(1)}$	3.46$^{(1)}$	13.58$^{(1)}$	100.52$^{(1)}$
Natural gas	42.60$^{(1)}$	4.22$^{(1)}$	13.58$^{(1)}$	169.21$^{(1)}$
Hydroelectric	30.09$^{(1)}$	2.00$^{(1)}$		
Others	1.89$^{(1)}$	6.00$^{(1)}$	5.081$^{(1)}$	81.40$^{(1)}$
Wind	0.03$^{(2)}$	3.36$^{(3)}$		
Solar	0.00$^{(2)}$	25.88$^{(3)}$		
Biomass	0.13$^{(2)}$	7.33$^{(3)}$		
Geothermal	0.08$^{(2)}$	3.05$^{(3)}$		

Data Sources: (1) TSI, 2005; (2) MENR, 2003; (3) NREL, 2005.

Table 3
BAU assumptions

Macroeconomic assumptions		Energy price growth rates	
Marginal productivity of capital	11.5%	*Electric price growth rate*	2.9%
Cost and utility discount rate	3.0% per year	*Non-electric price growth rates*	
Productivity growth rate	1.0% per year	Oil	1.9%
Labor force growth rate	1.0% per year	Solid	0.0%
Income growth rate	3.0% per year	Natural gas	2.6%
Population growth rate	1.3% per year	Others	1.4%
Household growth rate	3.7% per year	*Learning rate*	
Upper limit on imports	30.0% of GDP	Solar	20.0%
Lower limit on exports	20.0% of GDP	Bioenergy	15.0%
Value share of capital[a] (*sk*)	40.0%	Wind	8.0%
Value share of labor[a] (*sl*)	60.0%	Geothermal	3.0%
Value share of electricity[b] (*se*)	45.0%	*Income distribution share*	
Value share of non-electricity[b] (*sne*)	55.0%	$Income_1$	25.0%
Elasticity of substitution[c]	0.3	$Income_2$	20.0%
Capital/output ratio	3.0	$Income_3$	17.5%
Production function parameters		$Income_4$	20.0%
α: 0.02; β: 0.15; γ: 1.00		$Income_5$	17.5%

[a] in capital-labor pair.
[b] in energy aggregates.
[c] between energy pairs and primary factors.

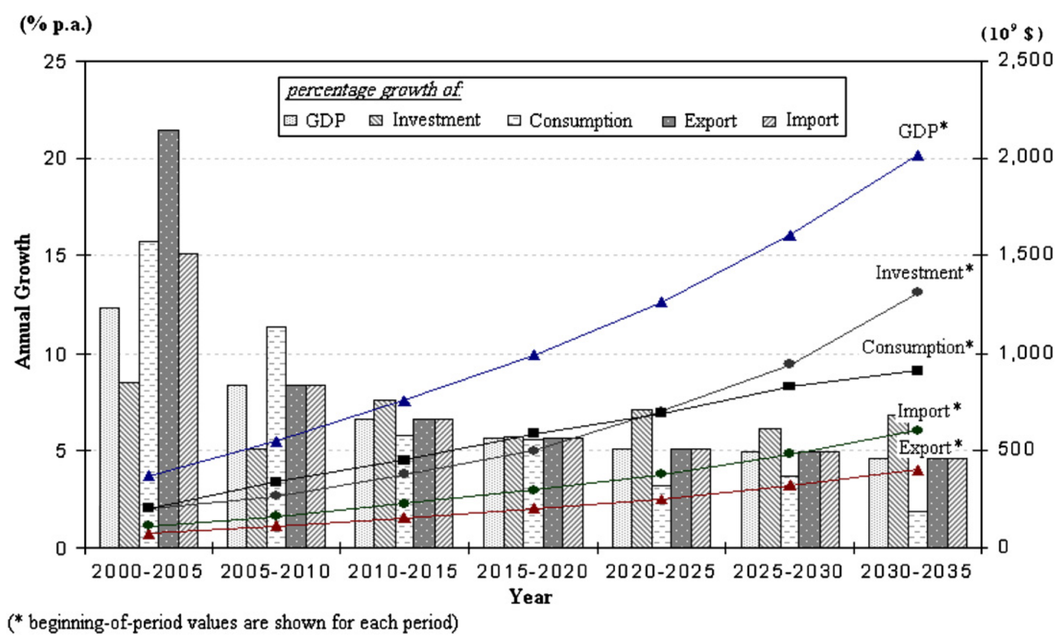

Fig. 2. Development of main economic indicators: BAU scenario.

source in the long run due to comparatively low generation costs, followed by bioenergy. The relatively high investment cost of solar PV makes it an unfavorable energy source. Prices remain high and therefore there is no additional installation of solar power in later periods, in spite of high learning rates.

The BAU relationship between WTP (for CO_2 emission reduction) and GDP in the planning horizon is illustrated in Fig. 3. The plot exhibits an exponential decline in WTP as a percentage of GDP. It shows that, although WTP increases as an absolute value, its share in GDP declines. However, as GDP grows, WTP stabilizes at about 0.065% of GDP.

4.3. Scenario analysis

In addition to the BAU scenario, various environmental scenarios including different CO_2 emission limitations, different learning rates for RETs and different income dynamics for WTP are defined as shown in Table 5.

The impact of the scenarios on GDP and fossil fuel demand are shown in percentage (Table 6) and absolute values (Fig. 5). As can be observed from Fig. 5, scenario ESS has the most dominant effects. It leads to a considerable economic shrinkage: the GDP loss of scenario ESS (compared to the BAU scenario) is roughly 17% in 2020 and 23% in 2030. The other scenarios lead to comparable economic losses when compared for a given year. The monetary equivalent loss in 2020, for example, amounts to 164.2 billion dollars in the BAU scenario and 164.1, 163.5 and 162.7 billion dollars for scenarios RES, SUS1 and SUS2, respectively. As the monetary values are quite close together, so are naturally the percentage losses (Table 6). This shows that neither an accelerated reduction in the cost of renewable power generation (scenario RES) nor an increased WTP due to a more wealthy population (scenarios SUS1 and SUS2) can bring a considerable reduction in the bill of reducing emissions. This is because of the necessity of huge investments to satisfy rapidly growing energy demand under severe CO_2 limitations (emissions limited to year 2005 levels). Environmentally sustainable (stabilizing CO_2 emissions to year 2005 levels) technology investments lead to an economic loss of about 20 billion dollars in 2010 gradually increasing to roughly 164 billion dollars in 2020 and 363 billion dollars in 2030. Are these costs implied by a significant change in the energy supply mix?

Yes, there are indeed significant changes in the technological composition of power generation (Fig. 4). Emission limitations induce a shift away from coal- and oil-based technologies towards hydroelectricity and natural gas-fired power generation. Electricity production from hydroelectric energy shows a rapid growth at an average annual rate of 4.3% after 2020. There is a total decline in fossil fuel utilizations by 19% in 2010, 39% in 2020 and 50% in 2030. Decline in electricity production from fossil fuel-based technologies is met by an increase in hydroelectricity and other new RETs. However, since the share of electricity produced by new RET other than hydroelectricity remains below 0.3% of total electricity consumption, it cannot be observed in Fig. 4. The low utilization rate of new RETs is in line with the findings of another study (Kumbaroğlu et al., 2007).

Even though the non-hydro RETs cover a narrow portion of total electricity consumption (Fig. 4), it is observed that each scenario leads to serious growth in the share of new RETs (Fig. 6). The share of non-hydro RETs grows at an annual rate of 5.2% from 2010 to 2020 and 26.5% from 2010 to 2030 in scenario ESS. The demand for RETs follows a higher trend in scenario RES than in scenario ESS, which is a direct implication of the doubling in learning rates. Scenarios SUS1 and SUS2 also induce new RET installation, but to a much smaller extent. Bioenergy, with an

Table 4
Electric and non-electric energy generation by primary energy source: BAU scenario

	2000	2005	2010	2015	2020	2025	2030	2035
Primary energy sources								
Oil								
Electric	7.19	10.66	14.37	18.34	22.56	27.06	33.05	39.35
Non-electric	346.91	434.94	530.4	633.69	745.19	865.32	1052.36	1248.93
Hard coal								
Electric	3.6	12.9	22.7	33.03	43.92	55.4	68.09	81.43
Non-electric	95.51	151.22	210.59	273.8	341.04	412.52	504.39	600.93
Lignite								
Electric	35.63	35.04	34.72	34.68	34.95	35.53	42.39	49.59
Non-electric	157.93	131.69	105.45	79.22	52.99	26.76	26.86	26.97
Natural gas								
Electric	42.6	61.06	80.82	101.95	124.53	148.61	181.39	215.84
Non-electric	157.91	250.02	348.17	452.67	563.85	682.03	833.91	993.53
Other								
Electric	1.89	1.67	1.45	1.24	1.04	0.84	0.96	1.08
Non-electric	59.09	48.95	38.79	28.61	18.42	8.21	7.83	7.44
Renewable electricity sources								
Hydro								
Electric	30.09	47.65	66.35	86.27	107.45	129.98	158.92	189.34
Wind								
Electric	0.03	0.06	1.14	1.49	1.52	1.56	1.6	1.64
Biomass								
Electric	0.13	0.13	0.14	0.14	0.32	0.57	0.92	1.4
Geotherma								
Electric	0.08	0.14	0.28	0.35	0.43	0.51	0.61	0.71
TOTAL								
Electric	121.23	169.3	221.97	277.49	336.72	400.06	487.92	580.39
Non-electric	817.35	1016.81	1233.4	1467.98	1721.48	1994.85	2425.35	2877.81

(Electric: TWh; Non-electric: Mtoe).

Table 5
Scenario definitions

Scenario	Description
Baseline	BAU: *business-as-usual*
ESS	Emission stabilization scenario: *emissions restricted to 2005 BAU levels*
RES	Renewable energy scenario: *ESS + doubling of learning rates*
SUS1	Sustainability scenario 1: *RES + 6% annual income growth + 40% increase in high-income class population share* (*and a corresponding decline in lower income classes*)
SUS2	Sustainability scenario 2: *SUS1 + 100% increase in high-income class population share* (*and a corresponding decline in lower income classes*)

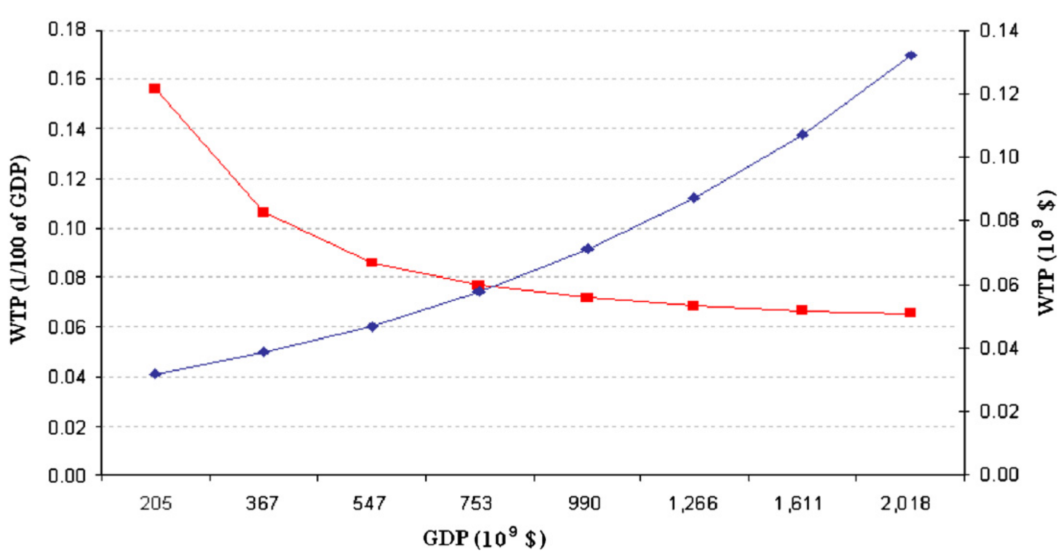

Fig. 3. GDP–WTP relationships under BAU assumptions.

Table 6
Percentage Reductions in GDP and Fossil Fuel Demand Compared to BAU

Year	ESS		RES		SUS1		SUS2	
	% GDP loss	% Demand reduction	% GDP loss	% Demand reduction	% GDP loss	% Demand reduction	% GDP loss	% Demand reduction
2010	3.8	19.04	3.8	19.04	3.71	19.04	3.61	19.04
2015	11.69	30.85	11.69	30.85	11.62	30.86	11.54	30.87
2020	16.8	38.95	16.8	38.95	16.73	38.95	16.65	38.95
2025	19.58	44.14	19.57	44.14	19.51	44.14	19.44	44.14
2030	22.83	50.46	22.83	50.46	22.78	50.46	22.71	50.46
2035	25.39	54.64	25.39	54.64	25.35	54.64	25.31	54.64

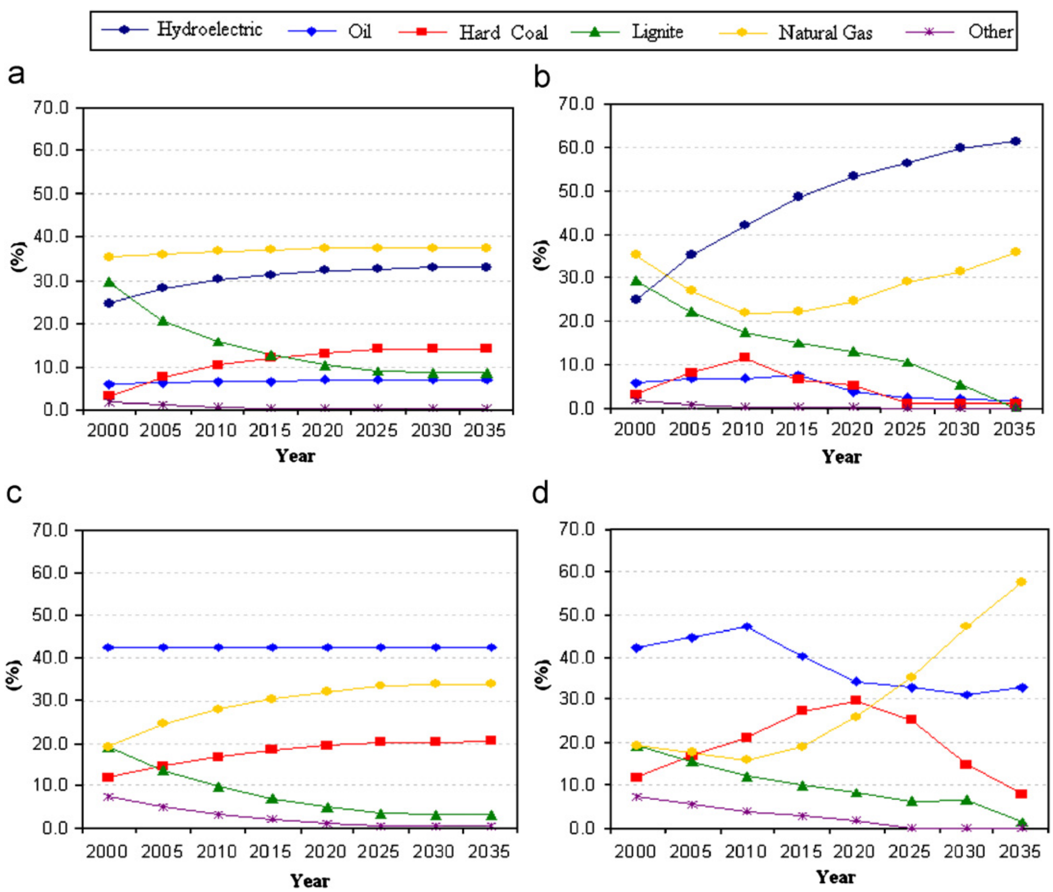

Fig. 4. Comparison of energy compositions: BAU and ESS scenarios. (a) BAU Electric Energy Composition, (b) ESS Electric Energy Composition, (c) BAU Non-Electric Energy Composition, (d) ESS Non-Electric Energy Composition

average growth rate of 33% p.a., is the most preferred RET in scenario SUS1. However, geothermal energy becomes the runner in scenario SUS2. The average geothermal growth rate for scenario SUS2 is obtained as 44% p.a. In SUS1, a doubling of learning rates and 6% annual income growth cause the share of new RETs in total energy consumption to increase by 41% in 2020 and 171% in 2030 compared to BAU scenario.

4.4. Model sensitivity to key parameters

Model sensitivity to the cost and utility discount rates, learning indices and WTP value, as well as to the growth rates of labor force, electricity price, oil price and gas price is explored. As expected, the lower the utility discount rate, the higher the value placed on the future utility and the higher the growth in consumption. The faster the labor force growth, the higher the GDP. The higher the energy prices, the lower their demands. The impact of such usual observations on model results remains within reasonable limits ($\pm 10\%$), being more emphasized in latter periods. Detailed results of such sensitivity analyses can be found in Karali (2006).

Our sensitivity focus in this paper is on RETs: the impact of technological learning and WTP on RET diffusion. Learning curves, obtained from the sensitivity analysis on different learning indices for the same ratio of increase in cumulative production, are shown in Fig. 7. An increase in the learning index of any renewable energy technology leads to a more rapid cost reduction. In other words,

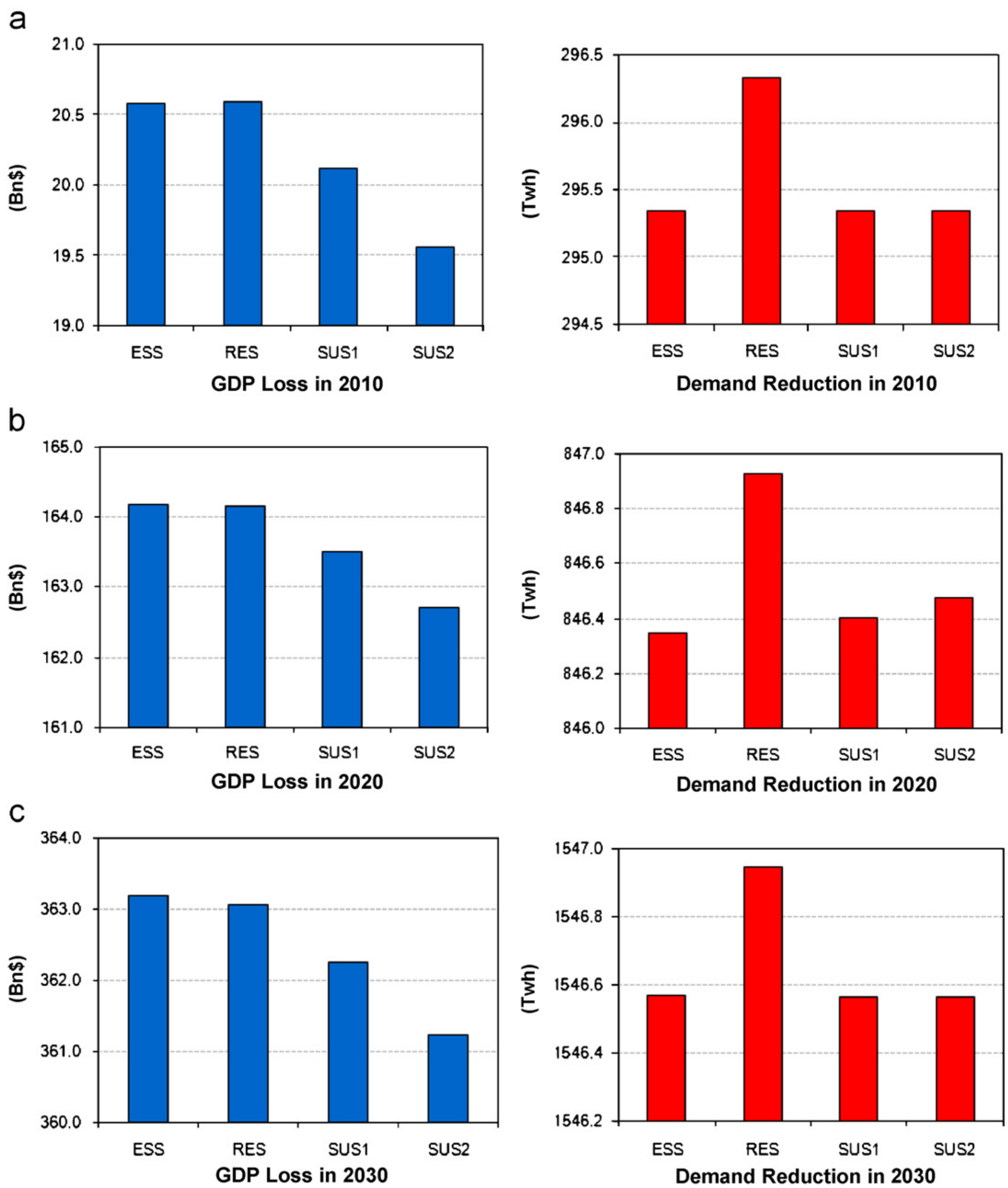

Fig. 5. GDP loss (left panel) and fossil fuel demand (right panel) reduction compared to BAU.

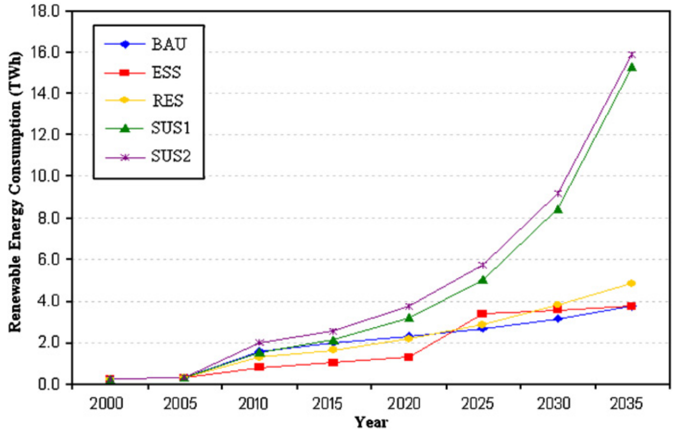

Fig. 6. Development of new (non-hydro) RET generation (TWh).

higher learning indices accelerate the decline in cost for the same cumulative capacity level.

Since the nature of the WTP function is subjective due to the limited coverage of the underlying questionnaire, there is a need to explore the sensitivity of results to WTP assumptions. Fig. 8 shows RET consumption values in response to four alternative WTP assumptions. In addition to a "No-WTP" run, there are two runs taking a constant WTP value for the whole planning horizon (WTP = 0.05 and 0.10), and a run assuming the same WTP trajectory as under BAU but with WTP values being doubled ($2 \times$ WTP). Naturally, the net effect is to decrease or increase RET consumption as WTP becomes lower or higher, respectively. When consumers are willing to pay a constant value of 0.05 billion dollar to reduce CO_2 emissions, there is almost a 35% reduction of RET demand in each time period. It is found that the installation of RETs increases at an average rate of 102% per period when there is a doubling in WTP. In other words,

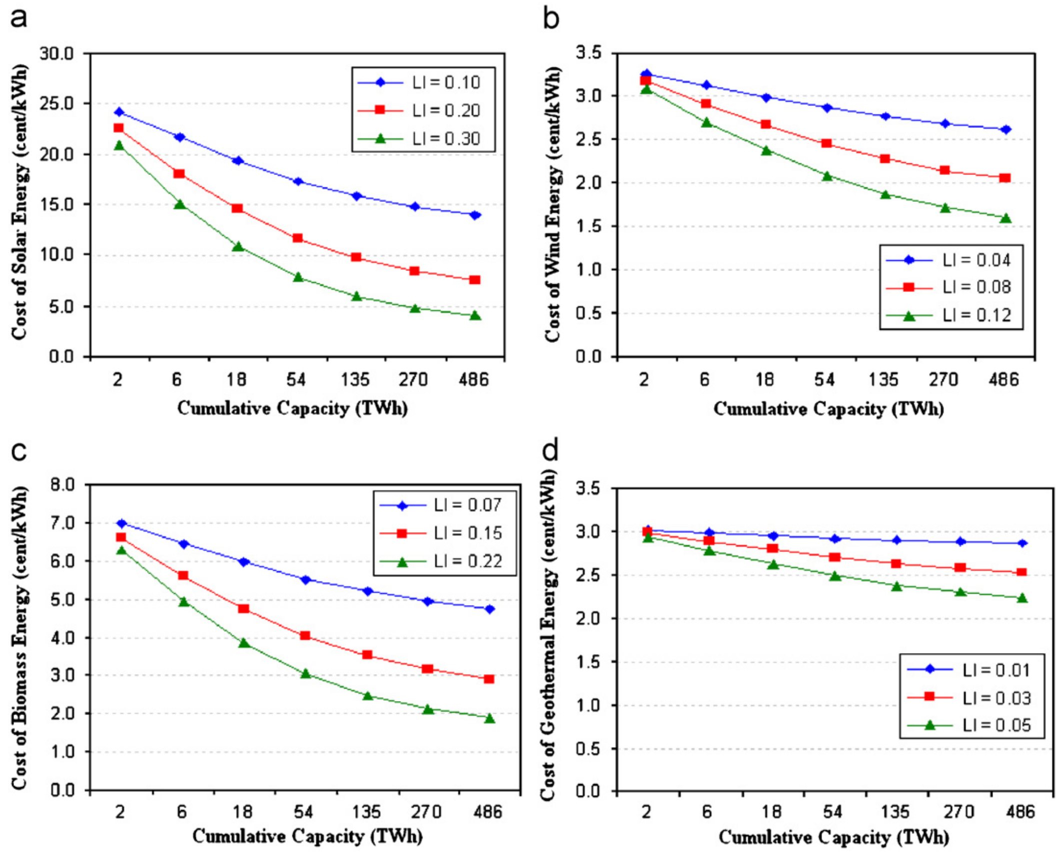

Fig. 7. Learning curves for RETs.

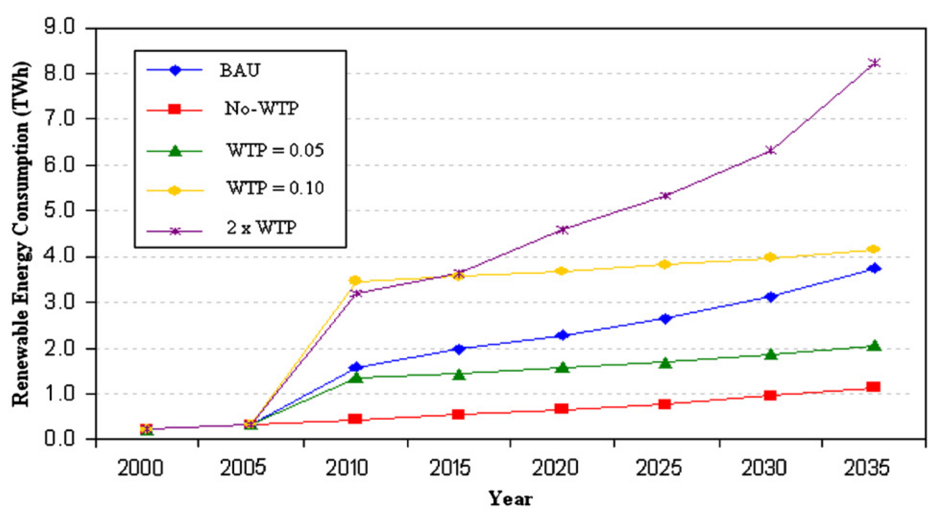

Fig. 8. Model sensitivity to various WTP values.

RET installation almost doubles each period when there is a doubling in WTP. In spite of a significant impact on RET installation, the impact of WTP on macroeconomic indicators remains negligibly small.

5. Conclusions

In this paper, an AEE model is developed and calibrated to explore the economic costs of different policy measures to mitigate CO_2 emissions in Turkey. Interactions between the energy sector, economic growth and CO_2 emissions are investigated with respect to various environmental scenarios. The model incorporates technological learning effects for RETs, reducing their cost as installed capacity increases. Based on a curve derived from a pilot survey application, the WTP of consumers for CO_2 emission reduction is also taken into consideration.

In addition to a Base Case (BAU), a number of environmental scenarios are defined restricting CO_2 emissions under varying WTP and RET cost trajectories. Model results suggest various useful policy implications for an environmentally and economically sustainable development of the country and provide long-term prospects for effective and applicable energy policy solutions to foster investment into new RETs.

Results show that emission reductions significantly affect economic growth and induce technological changes in the energy supply mix. The GDP losses in the Emission Stabilizing Scenario (scenario ESS), where emissions are stabilized at year 2005 levels, amount to 17% and 23% of GDP (compared to the Base Case) in the years 2020 and 2030, respectively. This corresponds roughly to 164 billion dollars in 2020 and 363 billion dollars in 2030. The economic costs are due to major changes in the technological structure of the energy system. Fossil fuel utilization almost halves in 2030. The shrinkage in fossil fuel use leads to significant increase (nearly 30%) in the installation of RETs, particularly hydroelectric power plants. Natural gas faces an accelerated growth as a relatively clean energy source. These findings indicate that new technological investments, financial assistance and targeted policies are inevitable for a sustainable evolution of the energy sector.

When the learning rates for new RETs are doubled (scenario RES), RET penetration increases compared to ESS. However, the share of RETs in the total energy supply mix remains very small so that the GDP losses due to emission restrictions are not reduced.

When the annual income growth is doubled (scenario SUS1), usage of new RETs is encouraged through the increase in WTP with negligible impact on economic growth and on the conventional energy mix. A doubling of both learning rates and income growth in SUS1 implies that the share of new RETs in total energy supply increases by 41% in 2020 and almost fourfold (171%) in 2030 (compared to the Base Case).

Sensitivity analysis with alternative values of WTP for new RETs shows that the net effect is to decrease or increase new RET consumption as WTP becomes lower or higher, respectively. Impacts on economic growth and the conventional energy mix remain almost unchanged. These findings indicate useful hints for energy and environmental policy makers so as to steer the country into a path of sustainable development.

The economic costs of emission limitation are caused due to the necessity for expensive new technology investments to meet increased demand. Therefore, for a cost-effective reduction of CO_2 emissions in Turkey, it might be wise to give policy priority to limit the increase in demand (e.g. through energy efficiency improvements, increased energy conservation or lifestyle changes). Another option (which is beyond the scope of the current model setting) to reduce the economic cost of new technology investments in Turkey might be to issue emission reduction certificates and sell them in the international marketplace at a price that reduces the cost of clean technologies to a level competitive with conventional fossil-based technologies. It should be noted that the possibility of emissions trading is not included in this study as this is currently no option for Turkey. However, should Turkey ratify the Kyoto Protocol under a position so as to sell emission certificates, than the dream of an economically and environmentally sustainable development of the country could become a reality.

Obviously, there are various environmental, social and economic benefits of emission reductions. However, calculating these benefits calls for a totally different modeling framework that is considered beyond the scope of this study. The exogenous calculation of benefits from each scenario enabling a cost-benefit analysis is possible.

Finally, as further research, it is necessary to widen the survey application so that the WTP equation is derived on the basis of a more solid empirical database. Another direction for model refinement is the endogenizing of income growth. Establishment of a linkage between income classes in the WTP function and other economic indicator variables in the macroeconomic sub-model will be a methodological improvement in the modeling framework.

Acknowledgment

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6. Appendix A

All parameters and variables which appear in the model formulation are defined below in alphabetical order.

A.1. Indices

k technology type for electricity generation
l renewable energy carrier type
m fuel type for non-electric energy generation
t time period

A.2. Parameters

a, b_i regression coefficients
l_i learning index
$c_{t,k}^{e}$ cost of electricity generation
$c_{t,m}^{ne}$ cost of non-electric energy generation
$c_{t,k=ren}^{r}$ cost of renewable power energy generation
ef_k^{elec}, ef_m^{nelec} emission factors
F_t factor incomes from abroad
HN_t total number of households
$IClass_{t,z}$ income class
L_t labour force
LN_t increment in labor force
P period length
sk, sl, se, sne value shares of capital, labor, electricity, and non-electric energy
TR_t tourism revenues
W_t workers' remittances
WTP_t willingness to pay
α_t, β_t, γ_t scale parameters
Δ_t annual discount rate
η_1, η_2 bounding factors
λ annual survival factor
ω annual growth rate of household number
ρ distribution parameter
σ elasticity of substitution

A.3. Variables

C_t consumption
CEC_t Total cost for conventional energy

Table A.1
T-test and confidence ınterval results

Independent variable	Regression		*T*-Value to test H0: $b_i = 0$	Reject H0 at 5%?	Power of test at 5%	Lower-95% confidence limit	Upper-95% confidence limit
	Coefficient b_i	Standard error					
Intercept	7.262	0.791	9.182	Yes	1.000	5.651	8.873
$IClass_1$	−5.575	0.928	−6.011	Yes	0.999	−7.464	−3.686
$IClass_2$	−5.243	0.945	−5.546	Yes	0.999	−7.168	−3.317
$IClass_3$	−4.708	0.969	−4.860	Yes	0.997	−6.682	−2.735
$IClass_4$	−5.527	0.945	−5.846	Yes	0.999	−7.453	−3.601
$IClass_5$	−4.329	0.945	−4.579	Yes	0.993	−6.254	−2.403

Note: the *T*-Value used to calculate these confidence limits was 2.037.

Table A.2
Analysis of variance

Model			Sum of squares	Mean		Prob level	Power -5%
Term	*DF*	R^2		Square	*F*-ratio		
Intercept	1		249.782	249.782			
Model	5	0.572	80.212	16.042	8.548	0.000	0.999
Income	5	0.572	80.212	16.042	8.548	0.000	0.999
Error	32	0.428	60.058	1.877			
Total (Adjusted)	37	1.000	140.269	3.791			

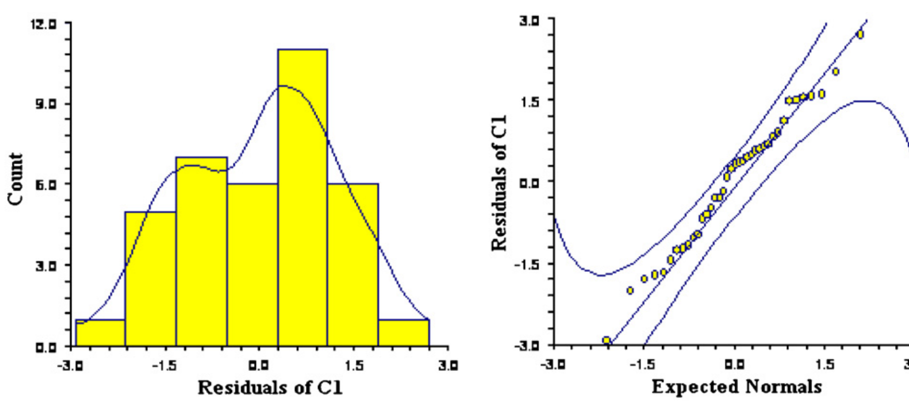

Fig. A.1. . Histogram and normal probability plot of residual.

$CO2_t$ carbon dioxide emission
$CUM_{t,k}$ cumulative production
E_t electricity
$ELEC_{t,k}$ electricity consumption
$ELECINC_{t,k}$ incremental capacity for electricity generation
EN_t increment in electricity
GDP_t gross domestic product
I_t investment
K_t capital
KN_t increment in capital
M_t import
NE_t non-electric energy
$NELEC_{t,m}$ non-electric consumption
$NELECINC_{t,m}$ incremental capacity for non-electric energy generation
NEN_t increment in non-electric energy
REC_t total cost for renewable energy
X_t export
Y_t gross output
YN_t increment in gross output

A.4. *Linear regression analysis on survey results*

Tables A.1 and A.2, and Figs. A.1 and A.2.

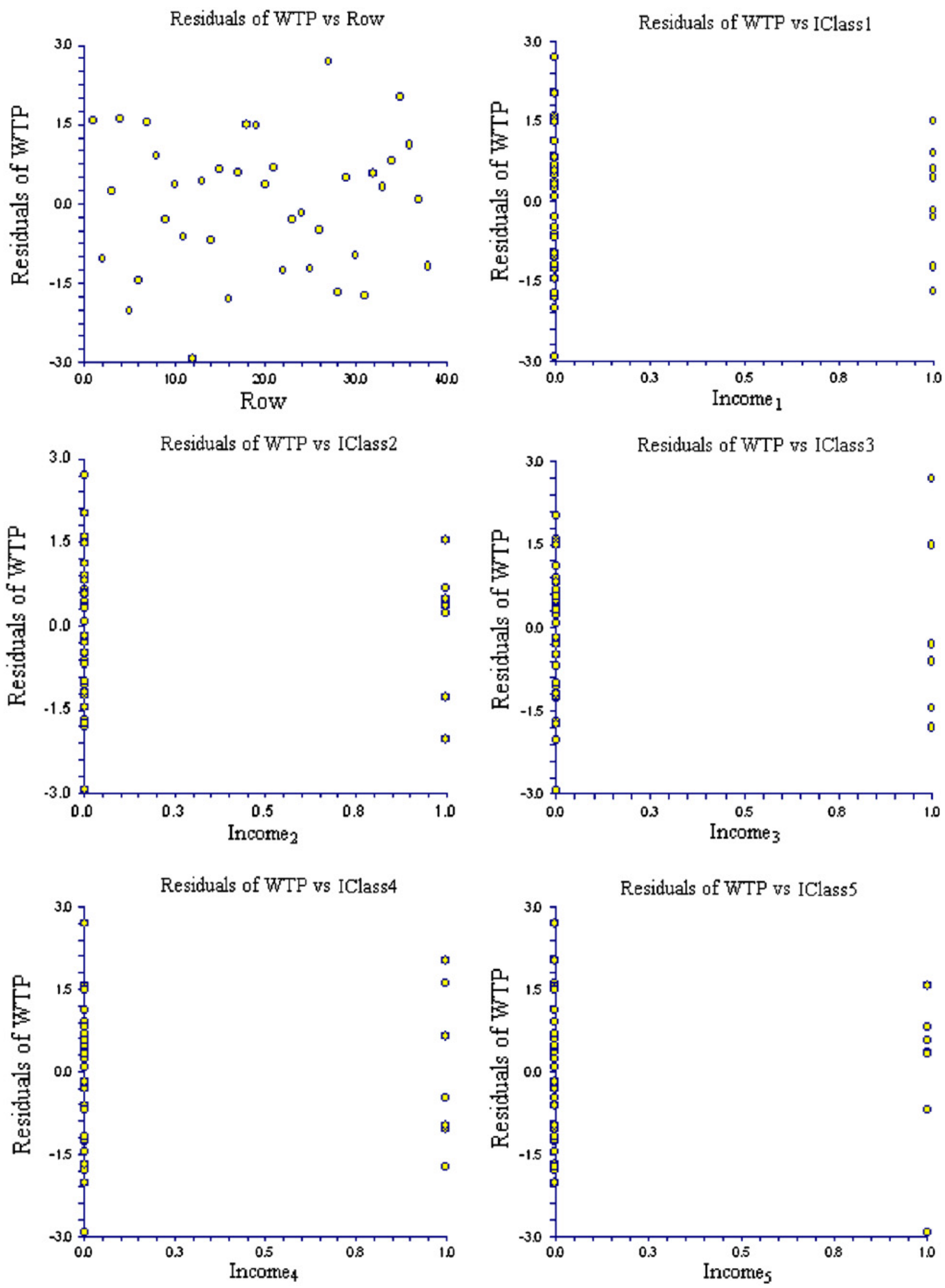

Fig. A.2. Scatter plots.

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