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Exploring the options for carbon dioxide mitigation in Turkish electric power industry: System dynamics approach

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HIGHLIGHTS

- An original computer model is created to investigate carbon mitigation.
- It is holistic and comprises investment, generation, dispatch, and resources.
- The model's structure, information base and foresights are specific to Turkey.
- Direct and indirect strategies are explored and integrated.
- Dramatic reductions are possible only with supply side strategies.

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ABSTRACT

Electric power industry has a huge carbon mitigation potential, fundamentally because there are large carbon-free, renewable resource options. In Turkey, with growing demand in electricity consumption and incentives offered for natural gas fired electricity generation, CO_2 emissions sourced from electric power industry had tripled over the last two decades. Current governmental strategy focuses on energy security and resource diversity in a growing economy and does not articulate sufficient mitigation targets and appropriate regulations. In this research, an original dynamic simulation model is built, validated and analyzed to explore the options for carbon mitigation in Turkish electric power industry. Model structure represents the investment, dispatch and pricing heuristics as well as the natural resource base of electricity generation in Turkey. It operates on annual basis over 30 years to simulate installed capacities and generations of power plants with alternative resources and their resulting CO_2 emissions. The analysis presented in this paper reveals that there are mitigation options below 50% of business as usual growth, with common policy options such as feed-in-tariffs, investment subsidies and carbon taxes. The model can serve as an experimental platform for further analysis of problems related to carbon mitigation in Turkish electricity sector.

1. Introduction

Carbon dioxide (CO_2) is the prominent greenhouse gas (GHG) that leads to global warming and climatic change with increasing concentrations above preindustrial levels. In the World average and in Turkey, electric power industry (EP industry) has the largest share in anthropogenic CO_2 emissions among other economic sectors. Because electricity can be produced by various means such as fossil fuel burning, nuclear fission and by harnessing of various carbon-free renewable energy resources (RES), there are strong options for carbon mitigation in EP industry, with different socio-environmental costs and benefits. Hence, considering its large resource alternatives, electric sector can respond to incentives aiming to reduce fossil fuel fired generation and can lead the way towards a low carbon economy (Ford, 2008a).

Turkey ratified UNFCCC in 2004 and Kyoto Protocol in 2009. However, arguing for its case for lower GDP, primary energy consumption and CO_2 emissions compared to those of OECD and other European countries on per capita basis (which are about four to five times higher on the average), it evaded being part of Kyoto's Annex B and did not declare quantified emission reduction targets (MEF, 2010). According to TURKSTAT (2011) Turkey's national vision within the scope of climate change is to "become a country which has integrated its climate change policies into the development policies, has let the energy efficiency become widespread, has increased the use of clean and renewable energy resources and, actively participates in the efforts for tackling climate change within the framework of its 'special circumstances'".

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Table 1
Turkey's key energy indicators compared to OECD and the World average (IEA, 2010a; TURKSTAT, 2011; MEUP, 2011).

Indicators	Turkey 1990	2008	OECD 2008	World 2008	Turkey % change
Population (million capita)	56.20	71.08	1190	6688	26.48
GDP (2000 USD/capita)	2.47	5.29	25.63	6.05	113.92
Primary energy supply (TOE/capita)	0.94	1.39	4.56	1.83	47.87
Electricity consumption (KWh/capita)	1024	2400	8486	2782	134.38
Energy intensity of the economy (TOE/2000 USD)	0.37	0.26	0.18	0.3	−29.73
Carbon emissions (tCO_2/capita)	2.23	3.71	10.61	4.39	66.36
Carbon intensity of the economy (tCO_2/2000 USD)	0.97	0.70	0.41	0.73	−27.84
Carbon intensity of primary energy supply (tCO_2/2000 TOE)	2.4	2.8	2.33	2.40	16.67

Although not strictly quantified and supplemented with appropriate policy instruments, MEF (2010) presents perspectives for controlling GHG emissions sourced from Turkish EP industry. Incentives for hydro and wind as well as for clean coal and nuclear power generation; efficiency gains in existing coal and hydropower plants are among the short and medium term perspectives on the supply side. A target in the longer term, which will be investigated in this study, is to increase the share of RES in electricity production to 30%, to achieve 20.000 MW of installed capacity in wind, 600 MW in geothermal and to fully utilize the nation's approximately 37.000 MW hydropower potential by 2023.

Together with possible gains on the demand side, compared to business as usual growth by 2020, MEF (2010) targets a 7% reduction in CO_2 emissions. Another target is to reduce the primary energy intensity in overall economy by 10% by 2020 (MEUP, 2011).

Carbon intensity of Turkish economy and the carbon intensity of Turkey's energy supply are higher than those of OECD countries and close to world average. Between 1990 and 2008, Turkey's key indicators on material and energy consumption and CO_2 emissions had doubled, and the carbon intensity of its energy supply increased. This has been due to a shift in electricity sector towards coal and gas based generation. Table 1 summarizes Turkey's key indicators of material consumption, energy supply and CO_2 emissions all in per capita basis, compared to OECD and World data and in historical perspective. The figures in the table are based on IEA (2010a) and TURKSTAT (2011) and the table is adopted from MEUP (2011).

The major source of CO_2 emissions in Turkey is fuel combustion in energy sector in general, and within the energy sector, electricity production in particular. Between 1990 and 2009, national CO_2 emissions from all economic sectors increased by 110% while the CO_2 emissions increase in the energy industries has been 114% (TURKSTAT, 2011). With this relative difference in growth rates, energy industries increased their share in CO_2 emissions from 32% to 35%.[1]

Fig. 1 depicts the annual development in EP installed capacity (TETC, 2011) and generation (TETC, 2010) with respect to primary energy resources used and also the resulting CO_2 emissions calculated by EC (2010). Data show that the three variables have been increasing over the last 20 years. This is due to EP industry's response to growing population and per capita electricity demand in Turkey.[2] Fig. 1 also illustrates that, coal, lignite, natural gas and hydropower (fossil fuel and hydro) constitute the major primary energy resources in electricity generation. Another fact is the increasing share of natural gas fired generation particularly after mid 1990s and corresponding decrease in the share of hydropower. Electric generation based on wind, geothermal and biomass is at negligible level. Photovoltaic and nuclear do not exist, though they are involved in the state plans. In 2010, about 65% of Turkey's installed base is fossil fuel powered and about 75% of its electricity is generated by fossil fuel burning. Ari and Koksal (2011) observe similar developments. Moreover, it can be argued that Turkey's case is similar to Latin American, where privatization in power generation without regulations and incentives for RES had lead to an increase in the share of gas based generation and to underutilisation of the continent's RES potentials (Arango and Larsen, 2010).

1.1. Sector structure in Turkey

Until 1980s, all segments of the electricity sector in Turkey were under state monopoly. In 1984, Law no. 3096 enacted private participation in generation with Build-Operate-Transfer (BOT) and Transfer of Operating Rights (TOOR) contracts. In 1993, by Law no. 4283, Turkish Electricity Institution (TEK), the state company integrating generation, transmission, sales and distribution functions of the electricity sector was divided into two companies, TEAS (Turkish Electricity Generation and Transmission Company) and TEDAS (Turkish Electricity Distribution Company). In 1997, Law no. 4283 enacted private sector participation in generation through Build–Operate–Own (BOO) contracts. The Electricity Market Law (no. 4628) in 2001 has been the critical step towards liberalization which radically changed the structuring of the sector. It aimed "financially strong, stable, transparent and competitive electricity market". With Law no. 4628, the Energy Market Regulatory Authority (EMRA) was established as an independent regulatory public organization. The same law further unbundled TEAS into three state owned companies: TEUAS (Turkish Electricity Generation Company), TEIAS (Turkish Electricity Transmission Company) and TETAS (Turkish Electricity Trading Company) which is responsible for the electricity wholesale from generators to distributers. Private participation is allowed in distribution as well as in generation but not in transmission.

Now, TEUAS owns about 49% of the national generation capacity, produces about 45% of the nation's electricity and this share is in decline with new privatization contracts (MENR, 2011). The distribution activity under TEDAS is fully privatized. Cetin and Oğuz (2007) discusses reasons why in spite of the Law no. 4628, the industry moves towards a more centralized structure and why the

[1] According to TURKSTAT (2011), energy industries comprise electricity generation and the use of fossil fuels for petroleum refining. CO_2 emissions from petroleum refining constitute 2.23% of the energy industries' emissions. In the year 2009, Turkey's CO_2 emissions from electricity generation (namely, from burning of lignite, natural gas, hard coal, residual fuel oil and diesel oil) is 96.27 Gt CO_2, that is 35% of overall national CO_2 emissions.

[2] TETC (2010) reveals that the electricity import and export of the country is less than 1% and 2% of the domestic generation respectively, indicating that the

(*footnote continued*)
observed growth in installed base and generation are responses to the increasing domestic EP demand.

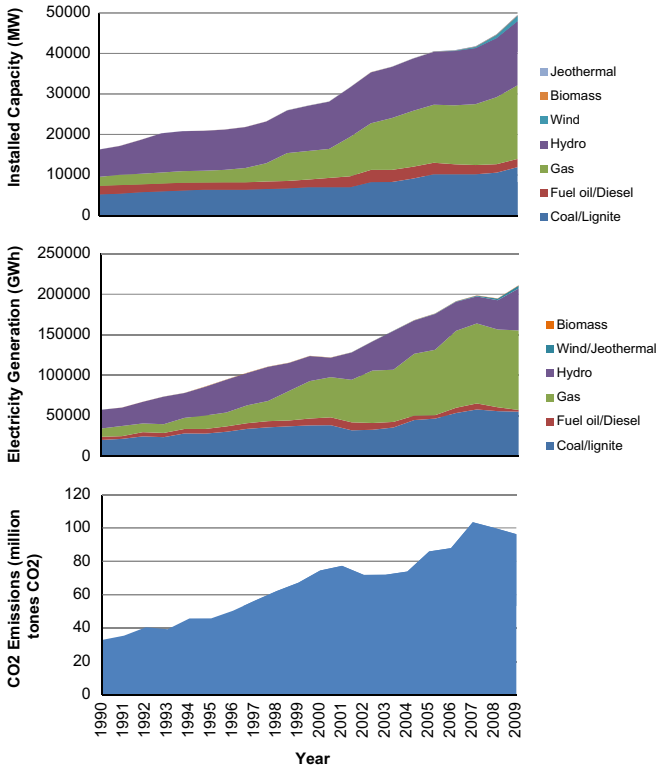

Fig. 1. Installed capacity (TETC, 2011), electricity generation (TETC, 2010) and resulting CO_2 emissions (EC, 2010).

liberalization of the industry is deferred to the future against these regulatory reforms.

1.2. Carbon mitigation in EP industry

Turkish EP industry is faced with a growing demand; had seen its fossil-fuel powered base and resulting CO_2 emissions notably increased over the past 20 years; and had a move towards liberalization and regulatory reform which has not been fully implemented yet. Under the current international vacuum for an enforceable treaty that would cap Turkey's GHG emissions in the future, the strategic interest of MENR focuses on supply security through resource diversity. With this perspective, the government's target is to harness all domestic RES (mainly hydro and wind) as well as non-renewable (coal) primary energy resources potential for electric generation by year 2023 and to start installation of 4000 MW nuclear power capacity by year 2014 (MENR, 2010). In the strategic plan, energy efficiency, CO_2 mitigation and other environmental considerations have lower strategic priorities. Major governmental documents, for example MEF (2010), MENR (2010, 2011), and MEUP (2011) do not spell sufficient targets and hardly consider necessary incentives and regulations which are the required instruments for mitigating CO_2 emissions sourced from the EP industry in a market economy.[3]

[3] Among these documents, MEUP (2011) declares the implementation of emission trading mechanisms contributing to cost efficient capping of greenhouse gas emissions as one of its strategic objectives. To achieve this objective, resuming negotiations to facilitate Turkey's participation in regional and global carbon markets and establishing a national carbon market until 2015 are set as two primary targets. The only economic incentive for renewable energy use that would help to reduce carbon emissions from electricity generation is the purchase guarantees enacted by the renewable energy law no. 5346 in the year 2005.

On the other hand, policymakers worldwide, consider a variety of targets, regulations and incentives (Ford, 2008a). Regulatory decisions such as fuel efficiency and emission standards, price driven incentives such as investment subsidies, tax credits, feed-in-tariffs, and carbon tax, or quantity driven incentives such as cap-and-trade schemes and tradable green certificates are among the instruments that are available to policymakers who aim at reducing CO_2 emissions created by electricity generation. Indirect strategies such as preferential permitting for RES projects, and infrastructure development for enhanced connection of distributed generation (DG) to transmission networks are other options available to policymakers aiming to increase the share of RES in electricity generation and to reduce CO_2 emissions sourced from EP industry (Bauknecht and Brunekreeft, 2008; Haas et al., 2008).

2. Purpose of the study

Strategy documents and policy briefs reveal an interest towards increasing the share of RES and reducing carbon intensity in electricity generation in Turkey. However, appropriate regulations, incentives and indirect strategies are not sufficiently explored to understand the consequences of alternative options and to encourage policymakers to take an action towards a low carbon EP industry. In the literature, there are studies analyzing RES in Turkey (Demirbaş, 2008; Yüksek, 2008; Onatan and Ersöz, 2011; Baris and Kucukali, 2012) and their penetration potential to EP industry (Kumbaroglu et al., 2008; Lise, 2009. Studies explicitly addressing the problem of CO_2 mitigation in electricity generation are rare.

Among them, Ari and Koksal (2011) estimates CO_2 emissions from fossil fuel power plants between 2009 and 2019, based on the projected generation capacity of EMRA and ad hoc generation scenarios representing business as usual, fossil fuel based, gas based and renewable based future developments. They do not address regulations, incentives and indirect strategies that would help policymakers and the EP industry to arrive at specific emission targets. EREC and Greenpeace (2009) provide a comprehensive long-term analysis of primary energy resources use with ambitious mitigation targets. Their analysis is motivated by the argument that, so as to keep the increase in average global surface temperature levels below 2 °C above preindustrial levels, per capita CO_2 emissions worldwide has to be reduced to 1.1 t by year 2050. The change in this study is tuned towards this 1.1 t per capita emissions target. They consider all sectors of the economy exploiting primary energy resources. The mitigation leverage is the energy efficiency in demand side and resource substitution in supply side.

The purpose of the present study is to analyze the options for CO_2 mitigation in Turkish EP industry with a focus on capacity replacements by RES and change in capacity use in fossil fuel powered plants. For this purpose, a dynamic simulation model (a system dynamics model) is built, representing the investor behaviour and production processes of power plants based on primary energy resources (of coal, gas, hydro-dam, hydro-river, wind, bio-fuel and solar) comprising the existing and significantly potential resource options for the Turkish EP industry. The model generates annual average dispatch and electricity sales from individual resources. Demand growth is calibrated to EMRA (2010) scenario. Moreover, resource limits of RES and DG connection constraints (for hydro-river, wind and solar resources) are considered. CO_2 emission is a function of electricity generation from coal and gas fired power plants. The model analyzes the replacements and capacity use under price driven incentives of feed-in-tariffs, investment subsidies, tax credits, and carbon tax and indirect strategies of preferential permitting and available DG connection to networks between 2010 and 2030. The findings are compared to those of Ari and Koksal (2011) and EREC and Greenpeace (2009) as well as to the targets in MEF (2010).

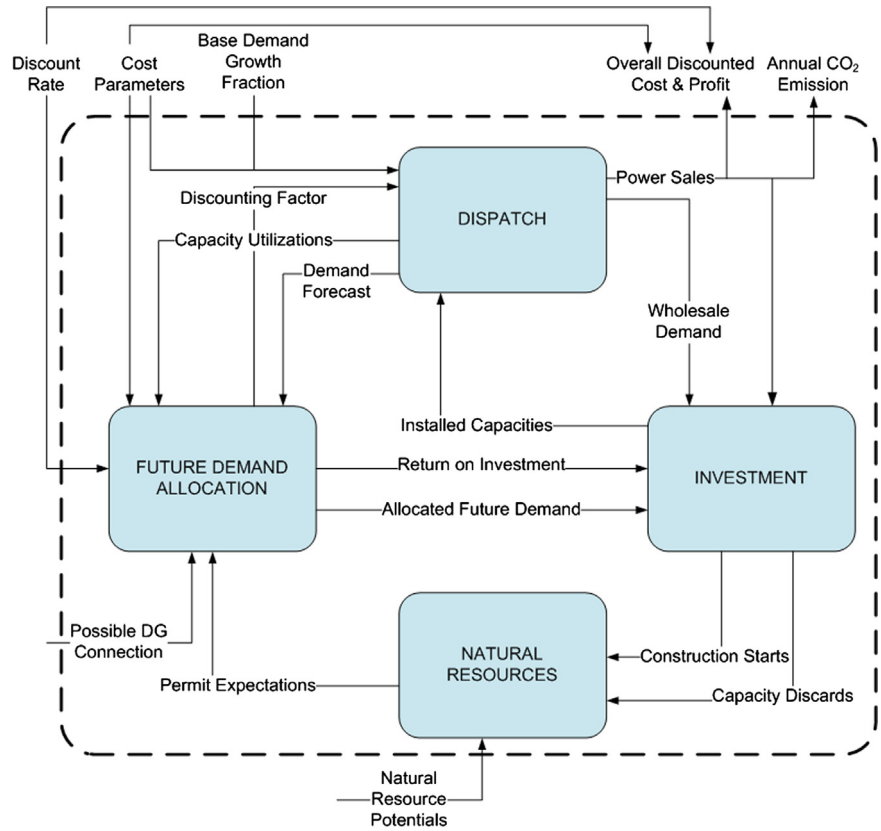

Fig. 2. Model structure overview.

3. Methodology

The methodology is *system dynamics* and the approach to carbon mitigation analysis is similar to that in Ford (2008b). System dynamics (dynamic feedback modelling) is a systems modelling and dynamic simulation methodology for analysis of dynamic complexity in socio-economic and bio-physical systems (Sterman, 2000). It has been widely applied to problems of electric power industry for investment planning (Ford and Bull, 1989; Ford, 1990; Naill, 1992; Olsina et al., 2006; Assili et al., 2008; Ben Maalla and Kunsch, 2008; Dyner and Larsen, 2001); for analysis of capacity cycles in deregulated markets (Bunn and Larsen, 1992, 1994; Ford, 1999, 2001; Arango, 2006; Dyner et al., 2009) and for carbon mitigation (Naill et al., 1992; Ford, 2008b; Ford et al., 2008).

4. Model description

Fig. 2 depicts model structure overview. The model is composed of four structural components: *investment*, *dispatch*, *future demand allocation*, and *natural resources* sectors. Investment and dispatch are the two fundamental functions of any power generation system. The *investment* sector represents the capacity aging and investment heuristics (for coal, gas, hydro-dam, hydro-river, wind, bio-fuel and solar based generation). Wholesale demand, power sales, return on investments and allocated future demand are the sector inputs. The *dispatch* sector distributes demand onto different plant types and creates forecasted demand of the electric sector. The inputs to this component are base demand growth fraction, cost parameters depicted in Table 2 and installed capacities. *Future demand allocation* allocates the forecasted demand onto different plant types. Cost parameters, demand forecast, capacity utilizations, the expectation on future available permits and possible DG connection are the inputs. Energy generation potentials of renewable resources (of hydro, wind, bio-fuel and solar) are represented in the *natural resources* sector. Turkey's natural resource potentials depicted in Table 3, capacity discards and construction starts are the inputs to this model component. Finally, the model evaluates the *outputs*, CO_2 emissions from electricity generation and the overall discounted costs and profits.

Simulation length is 30 years between 2000 and 2030. 2000–2010 interval is used for validation purposes and 2010–2030 interval is used to create foresight. The model is built on Vensim (Ventana, 2008), the time step of simulation is in years and the numeric computation is in continuous-time basis.

4.1. Investment

Generation capacity ordering, construction and depreciation for seven resource categories in power generation are represented. A typical supply line structure is depicted in Fig. 3 for wind based generation. Capacity investment starts with permit acquisitions. Permits wait in the capacity-site-bank (stock) until constructions start or permissions expire (Ford, 2001). Construction starts are influenced by return on investments (ROI), permits expire if the constructions do not start within permit expiration time.[4] Constructions end in their specific construction times. Installed capacity is modelled in three age cohorts: new, medium-aged and old. The sum of individual depreciation and discard times is equal to the total capital lifetime.

The investment heuristic is as follows: permit acquisition is the minimum of available and desired permits. Desired permits (in

[4] With decreasing return on investments, investors become reluctant for new constructions. On the other hand, acquired licences do not last forever. Turkish Electricity Market Law (no. 4628, year 2001) states that, acquired licences expire in 2 years in case the plant construction does not start.

Table 2
Resource based plant parameters selected for model reference run. Data is based on IEA (2005, 2010b) and EC (2008).

	Overnight construction costs ($/KW)		Operation and maintenance costs ($/KW)		Fuel costs ($/GJ)[a]		Capacity factors	Construction times (year)	Capital lifetimes (year)	CO_2 emissions intensities (tCO_2/MWh)
	Base	Range	Base	Range	Base	Range				
Coal	1172	719–2347	28.67	10.63–110.85	2.74	0.1–2.91	0.80	4	40	1.262
Gas	424	364–1292	5.54	4.92–47.36	4.67	3.55–5.72	0.80	3	25	0.365
Hydro-dam	1541	1230–3650	3.43	3.43–124.63	–	–	0.40	4	40	–
Hydro-river	2639	2000–4800	90.15	21.94–124.63	–	–	0.40	3	40	–
Wind	1280	1000–1370	14.91	14.30–131.56	–	–	0.25	1	20	–
Biofuel	3140	2960–5760	245	237–334	–	–	0.80	1	40	–
Solar-PV	5000	4000–6000	115	111–121	–	–	0.09–0.24	2	20	–

[a] Converted to $/MWh in model calculations with the conversion factor 1 MWh = 3.6 GJ.

Table 3
Economically feasible renewable resource potentials selected for model reference run. Data is based on Hepbaşlı et al. (2001), WEC (2005) and MENR (2011).

	Economic potentials
Hydro	36,603 MW
Hydro-dam	25,453 MW
Hydro-river	11,150 MW
Wind	48,000 MW
Bio-fuel	2.6 MTEP[a]
Solar	15 MTEP[a]

[a] Figures are converted to MW in model calculations using the conversion factor 1TEP = 11,630 KWh and the respective capacity factors presented in Table 2.

MW/year) aim at compensating for the capacity loss through final depreciation while they try to adjust the capacity stocks with respect to several targets. Among these targets, future and current desired generation capacities (in MW) are identified according to current and future demands to be satisfied, based on specific theoretical capacity factors (Randolph and Masters, 2008). The investment heuristic anchors for the loss through final depreciations, while it adjusts for the discrepancy between actual and desired capacities of capital stocks that would satisfy current and future demands. A similar approach to utility investor behaviour is used in Kim et al. (2007). Several investment heuristics are studied in Sterman (2000, pp. 663-708).

4.2. Dispatch

Dispatch model generates annual electricity sales, calculates price, adjusts the demand based on calculated price and creates forecasted demand. Thus, capacity utilizations of specific plant categories are calculated in this sector. Based on cost parameters and installed capacities depicted in Table 2, electricity demand is dispatched to each plant type using a heuristic which mimics load taking/shedding activities in power systems. The heuristic executes demand dispatch to nearly minimize the total annual generation cost. It is outlined in Appendix A.

Average wholesale price is the weighted average of sale prices. Demand is adjusted with respect to wholesale price. Demand forecast is created with Vensim TREND function that estimates change in growth fraction within a specific forecasting horizon. Soon, in the *investment model*, to estimate the future capacity needs, forecasted demand is adjusted with *future demand supply ratio* which represents the demand-supply balance in the future and estimated by current depreciation rates, installed capitals, and under construction and site bank stocks.

4.3. Future demand allocation

So as to allocate future demand onto alternative resources, the concept of *attractiveness* is used. Thus, resources with higher relative attractiveness receive higher shares of future demand. Therefore, their desired future capacities and investments would be higher. Attractiveness is a function of return on investments (ROI), permit expectations for RES based power plants, and constraints on DG connections to the power grid.

In corporate finance, ROI is a common instrument to compare investment alternatives (Lyneis, 1980). In ROI calculations, expected revenue, expected depreciation rate, overnight construction and operational costs, and tax rates are considered. Permit expectations describe the expectations for available construction permits in the future for RES such as hydro, wind, bio-fuel and solar. Possible DG connection represents the suitability of the power grid for DG supply to the distribution networks, rather than to the high voltage transmission networks.[5]

4.4. Natural resources sector

Natural resource base and the permits for renewable resources are represented. Fig. 4 depicts the available capacity for wind (in MW). Available capacity increases with installed wind capacity discards and decreases with installed wind capacity constructions (in MW/year). Total countrywide potentials for renewable resources (available plus installed capacities) are presented in Table 3. *Available permits* (in MW/year) is the regulator's policy which depends on the available capacity. Desired and available permits determine the *permits availability* for specific RES that creates permit expectations for the investors. Permit expectations influence the relative attractiveness of individual resources.

The model outputs, CO_2 emissions (in $MtCO_2$/year) is calculated with a function of electricity generation from coal and gas fired plants (in MWh/year) and their respective carbon intensity parameters (in tCO_2/MWh) illustrated in Table 2. Overall discounted costs and profits are calculated by overnight construction and operational costs, and by total annual revenue.

[5] Hydro, wind, bio-fuel and solar power plants, often built in small scales and on remote sites are considered as DG. As their share in total generation grows to a significant level, it becomes difficult to accommodate this on the conventional distribution networks (Bauknecht and Brunekreeft, 2008). Therefore, the power grids need to be improved to accommodate larger share of DG. In the model base run, the existing capacity of the network for DG connection is accepted 20% of total generation being transmitted.

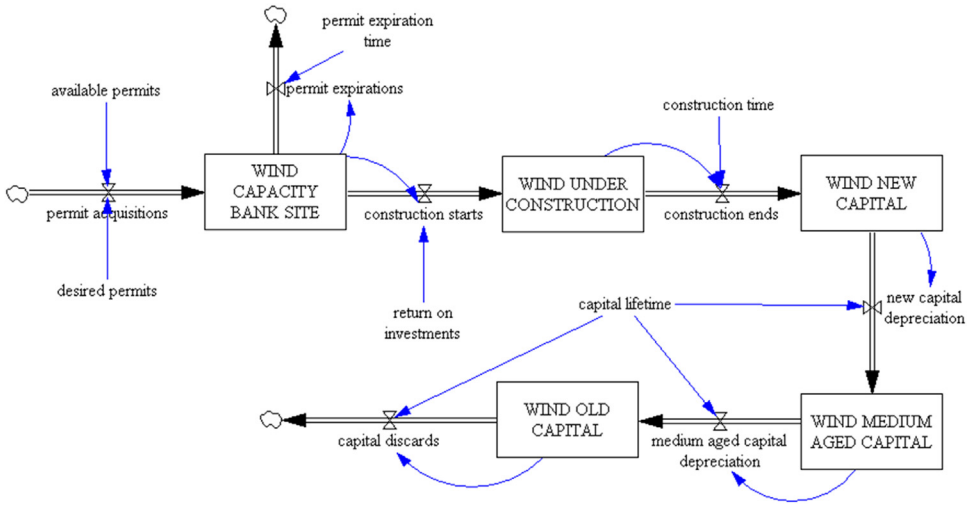

Fig. 3. Wind based generation capacity supply line.

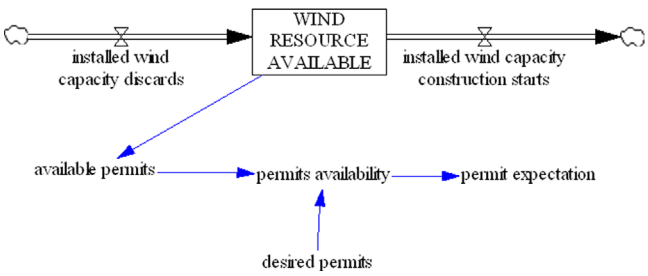

Fig. 4. Renewable resources availability.

5. Validation

Model validation in system dynamics consists of two critical sequential steps: validation of *structure* and validation of *behaviour*. Structure validation scrutinizes the internal consistency and sufficiency of the formal model elements for analysis of a set of selected dynamic problems. Behaviour validation seeks pattern match between historical data and model simulation outputs. Behaviour validation is performed after sufficient confidence is built in model structural validity (Barlas, 1996; Qudrat-Ullah and Seong, 2010). This sequence of model validation is followed in this study.

5.1. Structure validation

Along with semi-formal *direct* structure validity tests, *indirect* (simulation aided) structure tests are performed. Table 4 is a brief summary of the indirect structure tests (extreme condition and parameter sensitivity) conducted on specific model sectors and their inputs. Simulation outputs are not presented due to space restrictions.

In indirect structure testing, simulated model response must confirm logically anticipated behaviour (Barlas, 1996). This is how the tests in Table 4 are conducted. In the investment sector, if allocated future demand is increased, capital stocks increase and reach at higher levels with a time lag introduced by the material delays in the capital supply line. Higher construction times lead to higher under-construction stocks. Reduced capital lifetimes, on the other hand, lead to lower capital stocks. In the dispatch sector, increased fuel costs reduce the electricity generation of fossil fuel powered plants. Tests on O&M costs reveal similar results. Increased generation capacity of a particular plant type yields higher energy generation. It is observed that the dispatch sector response is robust under extremely high demand inputs. In FDA sector, overnight construction cost is the major cost element that determines ROI. It is observed that higher overnight construction costs yield lower construction starts. Increased capacity factors and increased marginal revenues increase ROIs and create higher constructions start rates. In the natural resources sector, when the available permits are increased, permit acquisitions increase.

5.2. Behaviour validation

Behaviour validity is tested through a multi-step validations procedure, which analyses the pattern match between simulated and observed data with specific statistics designed for comparing their trends, periods, phase lags, averages, and variances. For this purpose, the behaviour testing software, BTS is used (Barlas, 2006). The results show that, the simulated and observed data for installed capacities, generations and emissions are in good agreement with respect to above statistics. Moreover, although not very informative when presented detached from this comprehensive procedure, BTS provides summary statistics that may be useful for fast communication of its results. These statistics are provided in Appendix B. The behaviour fit between 2000 and 2010 is illustrated in Fig. 5 in the following section.

6. Model reference behaviour

Fig. 5 illustrates the model reference behaviour (generated in the base run) and its historical fit to TETC (2010, 2011) and EC (2010) between 2000 and 2010.[6] Demand between 2010 and 2020 is calibrated to low demand scenario of EMRA (2010). Base run cost and parameter choices are depicted in Tables 2 and 3. The discount rate (risk free interest rate) is 0.03, general interest rate applied to investment credits is 0.05. Tax rate deduced form earnings after depreciation is 40%. There are feed-in-tariffs confirmed by the Renewable Energy Law no. 4346 for hydro-river, wind, bio-fuel and solar based power generation between 2005 and 2030 (however set to their generation costs of 7.0, 3.6, 6.2, and 29.5 $cents/KWh respectively). Annually, 10% of unutilized natural resources are available as permits for RES based capacity construction and the transmission and

[6] Because, model structure does not represent fuel-oil/diesel powered power plants and the 600 MW of geothermal resource potential, the data used in calibration lack corresponding capacity and generation figures.

Table 4
Extreme condition and parameter sensitivity tests and their test inputs.

Model sectors			
Investment	**Dispatch**	**FDA**	**Natural resource**
Allocated future demand Construction times Capital lifetimes	O&M costs Fuel costs Demand scenarios	Overnight construction costs Capital lifetimes Capacity factors Marginal revenues	Available permits

distribution network can accommodate DG up to 20% of total generation. Therefore, base run foresight is sensitive to these assumptions.

Resource share in installed capacity and generation in 2010 and 2030 are depicted in Fig. 6. Installed capacity utilizations (for all resources) and resource utilizations (for RES) in 2030 are presented in Table 5. Table 6 summarizes key measures and annual CO_2 emissions. Model base run reveals that, the installed capacity reaches at 151,387 MW, total generation reaches at 569 TWh/year and CO_2 emissions reach at 255 $MtCO_2$ in 2030. The capacity share of fossil fuelled power plants has decreased from 64% to 48%. The increase in capacity share of RES based power plants is due to the increase in hydro-river, wind, bio-fuel and solar based capacity shares. In generation, the fractional share of fossil fuelled power plants is reduced from 78% to 64%. Similarly, the increase in RES based generation fraction is due to the increase in hydro-river, wind, bio-fuel and solar based generation shares.

Capacity and resource utilizations are depicted in Table 5. Capacity utilization in fossil based generation and hydro-dam are around 70% while hydro-river, wind, biomass and solar capitals are fully utilized because there are feed-in-tariffs that start in 2005 and last until 2030. Resource utilization in hydro reaches at 73% (i.e. 73% of natural resource capacity in hydro is utilized). Bio-fuel resource utilization reaches at 75% while for wind and solar, it is at medium levels.

As illustrated in Table 6, industry operates with a reserve margin 0.29 (i.e. the maximum possible generation is 29% larger than the demand), wholesale electricity price is 6.53 $cent/KWh (in 2010 it is around 5.5 $cent/KWh). Net present costs and profits of the whole EP industry (excluding transmission, distribution and other transaction costs) that accumulate between 2000 and 2030 are 286.98 and 150.07 billion $ respectively (yielding 0.52 profitability ratio).[7]

CO_2 emissions estimate of the base run is less than that in Ari and Koksal (2011) because the RES based capacity and generation in their BAU and RES scenarios are arbitrary and higher than that is generated in the base run.[8] MEF (2010) targets 30% share of RES in generation, 20,000 MW capacity in wind and 37.000 MW capacity in hydro by year 2023. Model generated values are 38%, 12,742 MW and 21,430 MW respectively. Although the base run created RES generation share is above the target, the capacity targets for wind and hydro fall short. Because, in the base run, there are significantly high feed-in-tariffs paid for bio-fuel and solar based generation which promotes alternatives among other RES.

Table 7 depicts the difference in model generated estimates and those in EREC and Greenpeace (2009) for 2030. In EREC and Greenpeace (2009) there are significant gains in demand side efficiency, which is not considered in current analysis. Therefore, in the model base run output, electricity demand, installed capacities and generations as well as CO_2 emissions are significantly higher. Moreover, electricity production costs are different because, base run does not assume gradually decreasing costs for RES. Still, it is interesting to compare the outputs of the two studies to observe how the 1.1 $MtCO_2$/capita/year emissions target of EREC and Greenpeace (2009) can be approached within the framework of current analysis.

7. Policy analysis

In policy analysis, first, results of price based incentives on RES are presented. Afterwards, the influence of putting price on carbon is investigated. Thirdly, the impact of fast permitting for RES and enhanced network availability for DG are discussed. Last, the results of an integrated approach to carbon mitigation are illustrated.

7.1. Price based incentives for RES

In this experiment, interest rates in investment credits and taxes on earnings for RES are effectively reduced to 0 after year 2012 (from 0.05 and 40% respectively in the base run). The *behaviour patterns* depicted in Fig. 5 do not change. Results are summarized in Tables 5–7. Because there are significant incentives for RES in the base run in the form of feed-in-tariffs, the system is insensitive to further incentives on RES in the form of investment and tax credits. On the other hand, this approach to carbon mitigation is expected to create significant public costs in the form of incentive payments and reduced tax earnings accumulating at around 50 billion $ discounted with over 18 years between 2012 and 2030. Therefore, this is not a feasible approach.

7.2. Carbon taxes

In this experiment, price is applied on CO_2 emissions in the form of carbon taxes, set to 2 cent/KWh for coal and 1 cent/KWh for gas after 2012. Behaviour patterns in Fig. 5 do not change. Focusing on the measures in 2030 (in Tables 6 and 7), wholesale electricity price is increased by around 1.5 cent/KWh, demand and fossil based generation is reduced, CO_2 emissions are decreased and electricity production cost is increased. Gradual increase in carbon taxes between 2012 and 2030 (not illustrated here) yield further change in the above measures in the same directions. This strategy is preferable over price based incentive on RES because it is expected to create public income in the form of taxes, accumulating to 40 billion $ with the same discount rate and along the same time horizon applied at above analysis.

7.3. Indirect strategies of fast permitting and enhanced DG connection

It appears that limited permits and restricted DG connection is a prominent impediment to increasing share of RES in capacity

[7] The figures tabulated in Tables 5–7 are the model generated values in 2030 and do not provide information about dynamic patterns. Indeed, because the model generates capacity cycles, for example, the reserve margin oscillates with a period of approximately 12 years.

[8] In Ari and Koksal (2011), CO_2 emission estimates in year 2019 are 198 $MtCO_2$/year for business as usual and 184 $MtCO_2$/year for renewable energy scenarios. Current model base run estimate for this figure is 143.

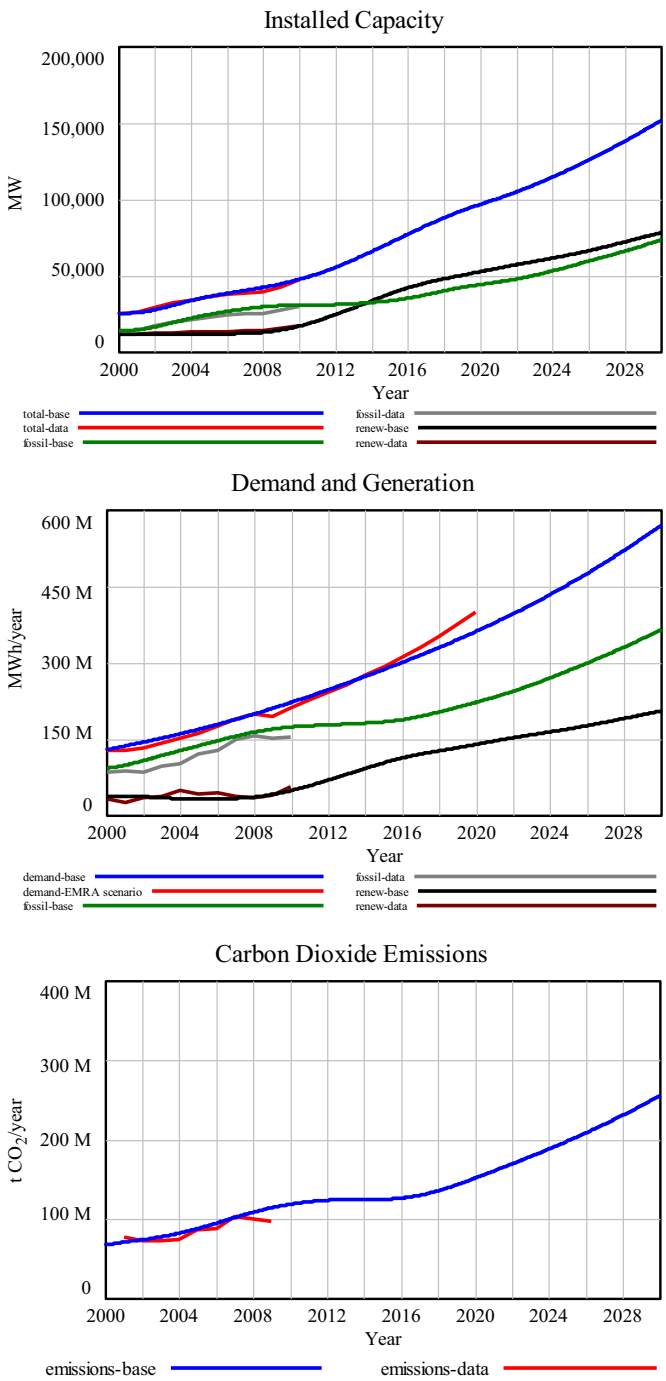

Fig. 5. Model reference behaviour and the historical fit.

and generation. In this experiment, annual permits in RES are equal to 40% of available natural resources and the network can accommodate DG up to 40% of total generation by year 2012. Compared to base run, resource utilization in wind and solar are increased, wholesale electricity price is increased and demand and total generation are decreased. The decrease in carbon emissions are more substantive, compared to the previous two policies. The model does not comprise assumptions on public costs of network capacity expansions for DG connections.

7.4. Integrated approach to CO_2 mitigation

The base run and the experiments inform an integrated policy, balancing price based incentives on RES, disincentives on fossil fuels with carbon prices and indirect strategies to promote RES and DG. This experiment integrates the elements used in previous three experiments, except annual interest rates in RES investment credits are reduced to 0.02 and taxes on RES earning are reduced to 25% (compared to 0.05 and 0.4 in the base run). Fig. 7 illustrates the behaviour patterns obtained in this experiment compared to the model reference behaviour. Total installed capacity has increased while fossil fuel powered capital has decreased. Total generation has decreased due to increased electricity generation costs, increased wholesale prices and reduced demand. Fossil based generation has decreased while RES based generation has increased. Reduction in CO_2 emissions is remarkable (by 42% compared to base run).

Comparing Figs. 6 and 8 yield further observations. Among RES, wind and solar significantly increase their shares in capacity, reaching at 19% and 35% respectively. This change is reflected in generation as well. Both for wind and solar, generation share reaches at 20%. Considering MEF (2010) targets, RES share in generation has reached at 60% (above target), wind capacity has reached at 21,154 MW (above target) and hydro capacity has reached at 25,135 MW (below target) in 2023.

Table 5 illustrates that resource utilization for all RES except wind are close to their maximum. In Table 6, electricity price is at its highest (10.00 $cent/KWh) and CO_2 emissions are at its lowest (138.4 $MtCO_2$/year). The aggregate net present cost of the industry has reached at 387.74 billion $ (35% increase compared to base run), indicating possible investment financing problems. On the other hand, because increased cost of electricity generation is reflected in prices, the profitability of the aggregate industry is equal to that in the base run (now, 0.53). Moreover, the possible public revenue from mitigation efforts, in the form of tax earnings minus investment subsidies and reduced tax incomes that accumulate over 18 years is 4.5 billion $. This indicates opportunities for investments in network capacity expansion for DG connection with public income generated through mitigation effort.

Yet, CO_2 reduction in EREC and Greenpeace (2009) is not achieved (see Table 7). On the other hand, doubling of carbon taxes (to 4 and 2 $cent/KWh) and decreasing interest rates and taxes applied to RES (to 0.1 and 10%) yield further reductions. Under such conditions, CO_2 emissions are reduced to 127 $MtCO_2$/year with wholesale electricity price equal to 10.83 $cent/KWh and public revenue generated through mitigation efforts accumulating at 5.8 billion $. It is observed that, even without significant demand side improvements, which are indeed essential for longer-term sustainable and cost effective reductions, dramatic CO_2 reductions can be achieved.

8. Conclusion

The role of regulations, incentives and indirect strategies in promoting RES and reducing GHG emissions from electric production is a well documented fact with examples from USA, Europe and Japan (Haas et al., 2008). In this study, we analyzed possible developments in Turkey along similar directions with simulation modelling and experimentation.

Base run in current analysis adopted several assumptions on demand, generation costs, financing, carbon intensities, feed-in-tariffs, RES permitting rates and DG allowances on distribution networks. Demand side efficiency improvements and possible reductions in future demand, retrofitting in existing capital and reduced carbon intensities, and possible change in cost parameters in construction and generation are not considered. Some of these questions can be answered through sensitivity analysis and direct experimentation with the current model, while some other questions require further model development and analysis.

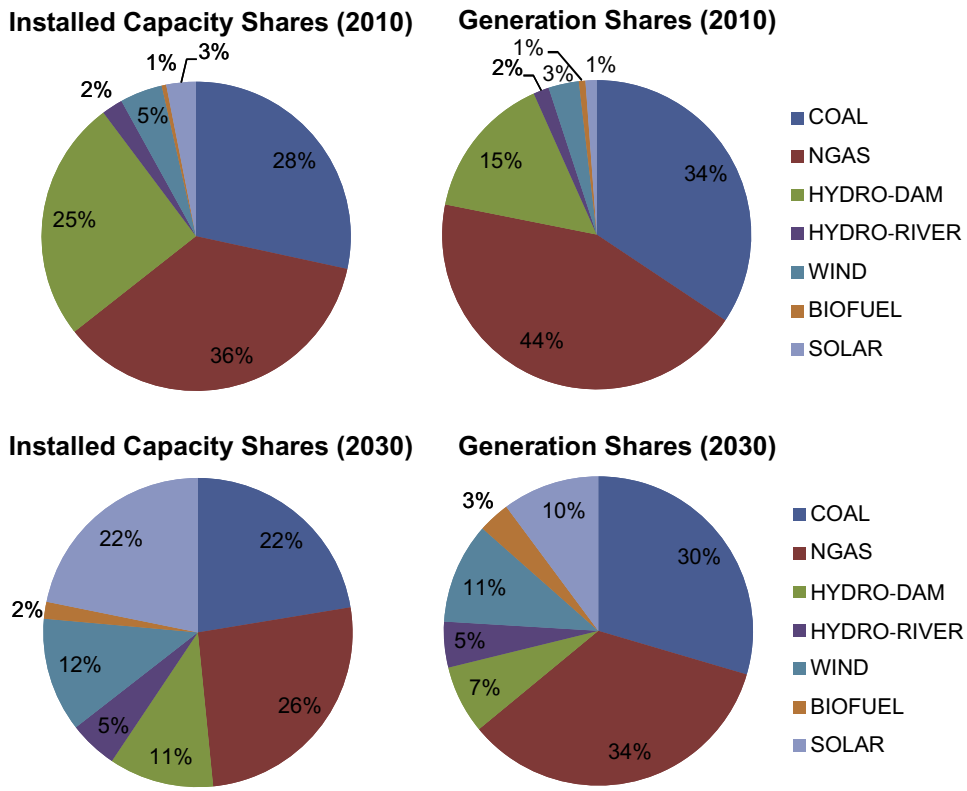

Fig. 6. Resource share in capacity and generation (base run—2010 and 2030).

Table 5
Capacity and resource utilizations (2030).

	Capacity utilization (fraction)							Resource utilization (fraction)				
	Coal	Gas	H-dam	H-river	W	B	S	H-dam	H-river	W	B	S
Base run	0.71	0.71	0.70	1	1	1	1	0.73	0.73	0.41	0.75	0.49
Incentives for RES	0.70	0.70	0.73	1	1	1	1	0.74	0.73	0.43	0.75	0.50
Carbon tax	0.69	0.72	0.73	1	1	1	1	0.72	0.73	0.38	0.75	0.45
Indirect strategies	0.71	0.72	0.70	1	1	1	1	0.71	0.74	0.58	0.75	0.61
Integrated approach	0.63	0.65	0.67	1	1	1	1	0.87	0.96	0.72	0.96	0.85

Table 6
Important measures (2030).

	Reserve margin (fraction)	Wholesale price (Scent/KWh)	Net present cost (billion $)	Net present profit (billion $)	CO_2 emissions ($MtCO_2$/year)
Base run	0.29	6.53	286.98	150.07	255.41
Incentives for RES	0.29	6.45	293.02	176.93	253.04
Carbon tax	0.29	7.94	288.15	168.77	232.22
Indirect strategies	0.25	7.6	331.78	168.06	209.78
Integrated approach	0.26	10.00	387.74	205.58	148.40

To test the impact of several assumptions on the created foresight, the model needs to be explored in a dialogical way, with the involvement of energy specialists, environmentalists, bureaucrats and sector managers. For instance, now in Turkey, there are strong conflicts over water resources, most of them triggered by river type hydropower plant constructions. While our integrated policy yields strong carbon mitigation, it utilizes whole RES potential suitable for river type hydropower plants, indicating a potential conflict between increased use of RES and carbon mitigation. Hence, the model can be explored as an experimental platform to evaluate the trade-offs between alternative goals and policies.

Analysis presented in this article reveals that, a delicate balance of feed-in-tariffs, investment subsidies, carbon prices, faster RES permitting and higher DG allowances help reduce CO_2 emissions dramatically below BAU levels without hurting the sector's overall profitability and creating public costs, however implying possible financing problems and increasing electricity prices. With

Table 7
Model outputs compared to EREC and Greenpeace (2009) energy revolution for 2030.

	EREC and Greenpeace	Base run	Incentives for RES	Carbon tax	Indirect strategies	Integrated approach
Total installed capacity (MW)	118,000	151,387	153,841	143,250	156,685	170,338
Fossil installed Capacity (MW)	58,000	73,302	73,351	69,104	60,151	46,911
RES installed capacity (MW)	60,000	78,085	80,490	74,146	96,534	123,427
Total generation (TWh/y)	415	569	573	538	551	525
Fossil generation (TWh/y)	242	364	361	341	301	210
RES generation (TWh/y)	173	205	212	197	250	315
Electricity demand (TWh/y)	450	569	573	538	551	525
CO_2 emissions ($MtCO_2$/y)	104	255	253	232	210	148
Electricity production cost ($cent/KWh)	8.2	5.55	4.35	6.42	6.65	8.06

improved demand side efficiency, reduced RES generation costs and increased fossil fuel prices in the future, absolute reduction in CO_2 emissions can be possible, leading the path towards what has been proposed in TURKSTAT (2011) for Turkey's role, as "actively participating in the efforts for tackling climate change".

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Appendix A. The dispatch heuristic

See Table A1 In dispatch, at each time period, electricity demand is assigned to power plants starting through the one with cheapest generation alternative. In other words, the demand assigned to each power plant is inversely proportional to its generation cost. This is what this dispatch heuristic mimics:

The inverse proportionality between energy generated by a plant and the ratio of its generation costs is formulated as:

$$\beta_i \propto \left(1-\frac{c_i}{\sum_j c_j}\right) \tag{1}$$

Demand–supply ratio D/S and scalar σ_1 are used to calculate fractional generations at each iteration.

Iteration 1: Calculate β_{i1} and σ_1:

$$\beta_{i1} = \left(1-\frac{c_i}{\sum_j c_j}\right) \times \frac{D}{S} \times \sigma_1, \tag{2}$$

$$\sigma_1 = \frac{1}{1-(\sum_j c_j s_j/(\sum_j c_j)(\sum_j s_j))}. \tag{3}$$

Note that when $D=0$, $\beta_i=0$. With σ_n, total demand becomes equal to total generation (a fundamental property of any dispatch algorithm). This condition is formulated in Eq. (10). Eq. (2) in iteration 1 does not guarantee that all $\beta_{i1} \le 1$. Hence in the second iteration, excess demand, given in Eq. (5), is re-distributed onto the power plants that have smaller-than-one fractional generation and new fractional generations are calculated in Eq. (7). This procedure is repeated until $\beta_{in} \le 1$ for all i.

Iterations 2 ... 7:

n.1: Define set Ω_n as the set of power plants with $\beta_{i(n-1)} \ge 1$:

$$\Omega_n = \{j : \beta_{j(n-1)} \ge 1\}. \tag{4}$$

$$\Delta D_n = \sum_{i \in \Omega_n} (\beta_{i1}-1)s_i, \tag{5}$$

$$S_n = \sum_{i \in \Omega_n} s_i. \tag{6}$$

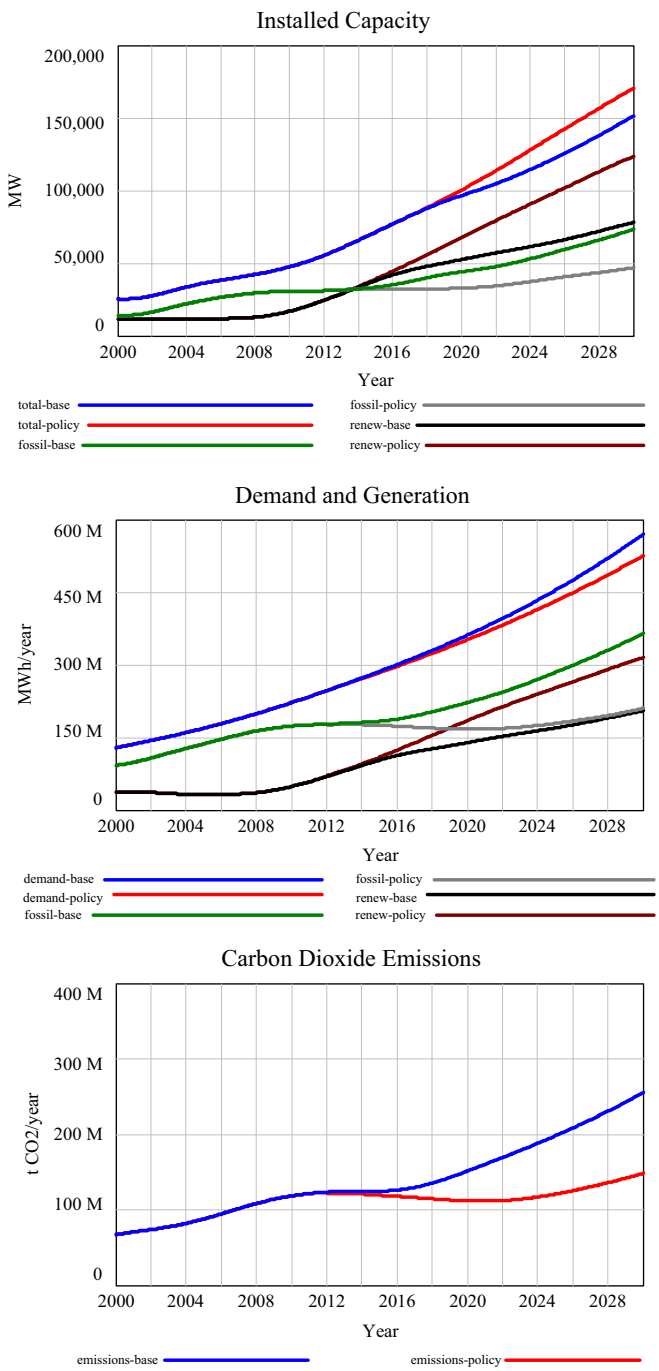

Fig. 7. Model behaviour (integrated policy).

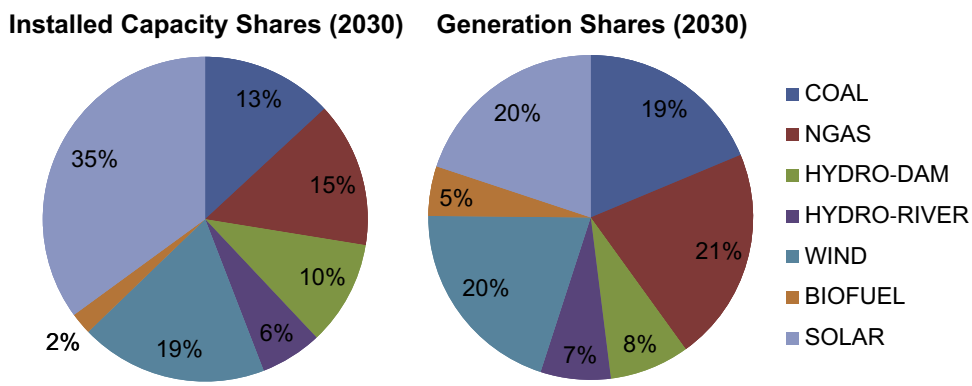

Fig. 8. Resource share in capacity generation (integrated policy—2030).

Table A1
List of notations.

β_i:	Fractional electricity generation of plant i
c_i:	Electricity generation cost of plant i (\$/MWh)
D:	Wholesale electricity demand (MWh/year)
S:	Total supply from all plant types (MWh/year)
s_i:	Electricity generation capacity of plant i (MWh/year)
σ_n:	Multiplicative scalar at iteration n
Ω_n:	Set including power plants with larger than one fractional generation (β_i) at iteration $n-1$
Ω'_n:	Complementary set of Ω_n
ΔD_n:	Unassigned excess demand from iteration $n-1$ (MWh/year)

n.2: Calculate $\beta_{i,n}$:

$$\beta_{i,n} = \beta_{i,n-1} + \left(1 - \frac{c_i}{\sum_{j\in\Omega'_n} c_j}\right) \times \frac{\Delta D_n}{S_n} \times \sigma_n, \quad \text{for all } i \in \Omega'_n, \tag{7}$$

$$\beta_{i,n} = 1, \quad \text{for all } i \in \Omega_n. \tag{8}$$

$$\sigma_n = \frac{1}{1 - (\sum_{j\Omega'_n}(c_j s_j)/(\sum_{j\Omega'_n} c_j)(\sum_{j\Omega'_n} s_j))}. \tag{9}$$

Note that the fractions $\beta_{i,7}$ satisfy the two conditions below:

$$\sum_i \beta_i s_i = D, \tag{10}$$

$$\beta_{i,n} \le 1, \quad \text{for all } (i,n). \tag{11}$$

It is verified that Condition 10 holds for ΔD_n in each iteration n, whereas Condition 11 is satisfied by Eqs. (7) and (8) in all iterations. Tests with real data indicate that this algorithm is a sufficient representation of annual power generation. A similar dispatch heuristic is used in Gumustas (2004).

Appendix B. Summary statistics for behaviour validation

	U	U^1	U^2	U^3
Total installed capacity (MW)	0.0172607	0.0000974	0.0828978	0.9170048
Fossil installed capacity (MW)	0.0138556	0.0000004	0.1672821	0.8327175
RES installed capacity (MW)	0.0101565	0.0024355	0.6781816	0.3193829
Total generation (TWh/y)	0.0327717	0.0002217	0.9564589	0.0433193
Fossil generation (TWh/y)	0.0171157	0.0011627	0.3006653	0.6981720
RES generation (TWh/y)	0.0237419	0.0014595	0.0930900	0.9054505
CO_2 emissions ($MtCO_2$/y)	0.0221453	0.0012676	0.9024513	0.0962810

U^1, U^2 and U^3 are Theil's inequality statistics.

$$U = \frac{\sqrt{\sum_{i=1}^{N}(S_i - \bar{S} - A_i + \bar{A})^2}}{\sqrt{\sum_{i=1}^{N}(A_i - \bar{A})^2} + \sqrt{\sum_{i=1}^{N}(S_i - \bar{S})^2}} = \frac{\sqrt{\sum_{i=1}^{N}(E_i - \bar{E})^2}}{\sqrt{\sum_{i=1}^{N}(A_i - \bar{A})^2} + \sqrt{\sum_{i=1}^{N}(S_i - \bar{S})^2}} = \frac{S_E}{S_A + S_S}$$

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