Coal Phase-out in the Turkish Power Sector towards net-zero emission targets: An Integrated Assessment of Energy-Economy-Environment Modeling

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Abstract

Power sector plays a crucial role towards decarbonization of the economies in line with the net-zero targets to limit global warming by 1.5 ℃. The technical constraints intrinsic to the sector, penetration of new technologies, investment and operational costs as well as its links with the rest of the economy make the power sector a complex system to analyze. Although there are numerous studies to integrate bottom-up power sector technology models and top-down macroeconomic models; this study is the first attempt to couple three separate models within a single framework: an electricity market simulation model, a generation expansion planning model and a macroeconomic applied general equilibrium model. Thus, the paradigms of power engineering, operations research, and economics of general equilibrium are holistically represented in the proposed framework in a way that combines the long-term dynamics consistently with the short-term hourly analysis. The proposed framework is implemented to analyze alternative scenarios aiming at successful phasing-out of coal-fired power plants in Turkey by year 2035. Our results suggest that, given the existing capacity and future potential of renewables, Turkey can achieve her coal-phase out by early 2030s, with 2035 at the latest. We also find that under the coal phase-out scenario, while real GDP and electricity demand increases by over 50%, installed capacity and generation of coal-fired power plants reduces by 62% and 70% respectively between 2018 and 2030, and is reduced practically to zero in 2035. Consequently, the CO2 emissions from power sector are reduced by 50% in 2030 compared to their 2018 level.

Keywords: Electricity market simulation model, Generation expansion planning, Applied general equilibrium, Coal phase-out, the Turkish power generation sector, Linear programming, Energy storage technologies

1. *Introduction*

Phasing out of coal has been one of the corner stones of the transition towards *net zero emissions* since the COP26 Glasgow Summit. Yet, given the complicated pathways of post-Covid recovery of global industrial production and the geopolitics of the Russian invasion of Ukraine, prospects for the pledged phase-out are rather gloomy. A recent report by International Energy Agency (IEA, 2022), for instance, forecasts that coal demand worldwide is expected to grow by "1.2%, reaching an all-time high and surpassing 8 billion tonnes for the first time in 2022"., to be driven by production records of the world's three largest coal producers – China, India and Indonesia.. Currently some 8,500 coal power stations, under 2,000 gigawatt installed capacity, are held responsible for one-third of the gaseous emissions globally. The IEA 2022 Coal Report further estimates that global coal power generation will increase by 2% in 2022. This comes over an expansion of 9% in 2021 to 10,350 terawatt-hours (TWh) which, in the words of the IEA, reflects *a new all-time high*. These numbers indicate that, the pre-Covid patterns of declining coal consumption in the advanced economies to be offset by the rising demand from the developing world, will likely to be revealed once again over the 2020s.

Turkey's share in global CO2 emissions is relatively low at around 1.2%. Yet, with a rate of increase of 3.3% annual growth in *per capita emissions*, (against the world average 0.65%), and a rapid rise of emissions from coal-based power generations jumping from 61 mtons to 164 mtons over 1990 to 2019, Turkey is regarded as one of the critical actors in the global design towards net-zero ambition.[1]

Turkey has also recently ratified the Paris Agreement in October 2021 and declared 2053 as the target year to achieve net-zero emissions. However, neither the action plans proposed officially, nor its currently revised Nationally Determined Contribution (NDC) document (announced at the 27th COP meetings in Sharm El Sheikh) comprises concrete interim plans on how to achieve its ultimate goals. Moreover, the European Green Deal and the concomitant carbon border adjustment mechanism (CBAM) will likely force the country to accelerate decarbonization efforts, especially starting with the power sector. The power sector in Turkey, with a share of 27.3% in total CO_2 emissions in 2019 (TURKSTAT, 2021), will certainly be the main actor in the energy transition strategies. The share of coal-fired power plants, on the other hand, is observed as the main source of the total emissions in the power sector given its share of 20.5% in installed capacity and 31.8% in generation (TEIAS, 2021). These figures lay bare the importance of modeling efforts that can thoroughly represent the power sector with its all aspects, i.e., environmental, financial, macroeconomic, and technological.

[1] IEA Greenhouse Gas Emissions from Energy https://www.iea.org/data-and-statistics/data-product/co2-emissions-from-fuel-combustion. Retrieved 30 January 2022.

There is a wide range of decisions (operational, strategic and political) needed to be taken in the power sector by the different agents, i.e., plant operators, system operators, investors and regulators. These decisions naturally differ in terms of their objectives, time-horizon, and technical complexities. These differences have also been reflected in the proposed models to seek answers so as how to instrumentalize the warranted transition of the sector. Over the course of time, researchers have reached a consensus that there are broadly two distinct, yet related, modeling approaches, top-down (TD) and bottom-up (BU) (Grubb et al., 1993). BU models represent the energy sector or any of its sub-sectors in technological detail with an extensive representation of the current practices and application of new technologies; while the TD models provide a detailed representation of the overall economy along with its links to other production sectors under the microeconomic foundations of optimization and macroeconomic flows. There is also a wide range of literature on integrating the TD and BU models. The integrated models are classified as soft-linked or hard-linked while hard-linking can be conducted in two ways (Kat, 2019), i.e., complete integration (Böhringer, 1998; Böhringer & Löschel, 2006; Böhringer & Rutherford, 2005, 2008) or integration of a core model with a reduced form model (Bahn et al., 1999; Kypreos, 1996; Manne, 1977; Manne et al., 1995; Manne & Richels, 1990; Manne & Wene, 1992). However, recent studies (Lanz & Rausch, 2011; Rausch & Mowers, 2012; Ross, 2014; Tapia-Ahumada et al., 2015; Tuladhar et al., 2009) mostly focus on coupling a generation expansion planning (GEP) model and an applied general equilibrium model (AGE) under the decomposition approach proposed in (Böhringer & Rutherford, 2009).

In line with the modeling trends summarized above, a set of models has been developed for analyzing the energy and power systems in Turkey. There are several stand-alone GEP models proposed for analyzing various policy options, objectives or challenges such as nuclear power, natural gas dependency, renewable transition, carbon taxation or uncertainty (e.g., Kat, 2021; Kilickaplan et al., 2017; Ozcan et al., 2016; Yildirim & Erkan, 2007; Selcuklu et al., 2023). Market simulation (MS) models, on the other hand, are smore limited in which the implications of penetration of renewable technologies on the capacity mix, transmission expansion and system flexibility are analyzed, (Aksoy et al., 2020; Godron et al., 2018; Saygın et al., 2019). There are also applied equilibrium models focusing on the macroeconomic impacts of energy policy issues in Turkey, i.e., studies of low carbon pathways, sectoral emission reduction policies, coal subsidies and CBAM, (Acar et al., 2021; Acar & Yeldan, 2016; Telli et al., 2008; Yeldan & Voyvoda, 2015).

In addition to the separate and individual modeling efforts, there have been significant attempts on integrating TD-BU models for Turkey (Fathurrahman, 2019; Kat, 2011; Kat et al., 2018; Şahin et al., 2021; Taranto et al., 2021). Kat (2011) constructs an integrated model in the optimization framework in which a detailed representation of the Turkish energy sector is coupled with five non-energy sectors. The proposed model is used for analysis of several scenarios including a nuclear program, carbon capture and storage technology, overall and sectoral emission quotas. Kat et al. (2018), on the other hand, proposes a power sector detailed computable general equilibrium (CGE) model, TR-EDGE, based on the GTAP Power database (Peters, 2016) in which the Paris Agreement goals of Turkey are assessed. Taranto et al. (2021) couples a modified version of TR-Power GEP model that was developed in (Kat, 2021) with an applied general equilibrium model that focuses on socioeconomic impacts especially in terms of labor. Fathurrahman (2019) proposes an integrated model that couples a computable general equilibrium model with a linear programming scenario generation model and a bottom-up scenario analysis energy model LEAP (Heaps, 2016). Finally, Şahin et al. (2021) prepares a roadmap that addresses the transformation needed in Turkey's economy following the ratification of the Paris Agreement and 2050 Net-Zero targets.

The model developed in this paper can be classified under soft-linked models in the aforementioned genres where a GEP model is linked to an AGE model. However, the main contribution of the modeling framework designed here is to employ two separate BU models for the power sector: a technologically detailed GEP model for long-term investment plan and an MS model for ensuring the technical feasibility of the annual expansion and operation plans generated by the GEP model. The motivation behind such a framework, specifically utilizing an additional BU model, i.e., the MS model, can be summarized as follows:

- Most of the BU components in the integrated models are linear GEP models in which most of the practical constraints (e.g., ramp-up ramp-down patterns, interconnection capacities, basic principles of power transmission and distribution) are represented with restrictive assumptions where most of these constraints are non-linear in practice. Integrating non-linear nature in the GEP models (which are already large-scale models with high number of variables due to hourly time resolution and multiple periods over the long-term) brings about computational complexities.
- The burden of computational complexity also forces the modelers to represent the power technologies in an aggregated fashion instead of a plant-wise or regional representation. This constraint would be very restrictive considering the significant differences across the plants and regions in terms of cost, efficiency, transmission/distribution capacity and renewable energy potential.
- GEP models are mostly solved to generate minimum cost investment plans over a long-term period. The objective of these models, then, represent the view of a hypothetical "central planner" which is not usually the case in practice. Although these projections are reliable benchmarks of the market actualizations in the long-run, the proposed approach allows GEP projections to be aligned with the market mechanisms via the MS model for which the underlying algorithm grounds on the merit order.

In addition to the aspects listed above, the energy storage technologies are extensively embedded into the proposed BU models that differs our study from earlier studies using previous versions of the GEP (Kat, 2021) and MS (Godron et al., 2018) models.

Besides the methodological contributions, our paper provides insights on one of the urgent and crucial topics to satisfy the declared 2053 net-zero target of the country, i.e., *coal-phase out in the power sector*. Noting that reaching net-zero by 2050s could not be a mere target to limit global warming by 1.5 ℃, it is also pertinent to indicate that assessment of the cumulative emissions on the pathway to net-zero, *i.e.*, carbon budget, is also critical. Although there are numerous studies on the abatement pathways for the coal-fired power plants or coal-phase-out for different countries and regions (e.g., Heinrichs et al., 2017; Ordonez et al., 2022; Keles & Yilmaz, 2020; Rentier et al., 2019; Li et al., 2017) there is a single modeling study on the coal phase-out in Turkey (APLUS-Energy, 2021). The study analyzes three scenarios, i.e., a business-as-usual scenario, a coal phase-out by 2030 scenario and a nuclear-free coal phase-out by 2030 scenario. The results show that coal phase-out by 2030 can be achieved with an additional cost of 1.1 billion USD directed to the renewable energy in addition to the nuclear energy investments.[2]

The rest of the paper is organized as follows. First, we present and overview of the Turkish power sector. Then, each individual sub-model and the proposed framework are explained. Next comes the scenario definitions and results. Finally, the paper ends with the conclusion and recommendations for future research.

2. An overview of the Turkish power sector

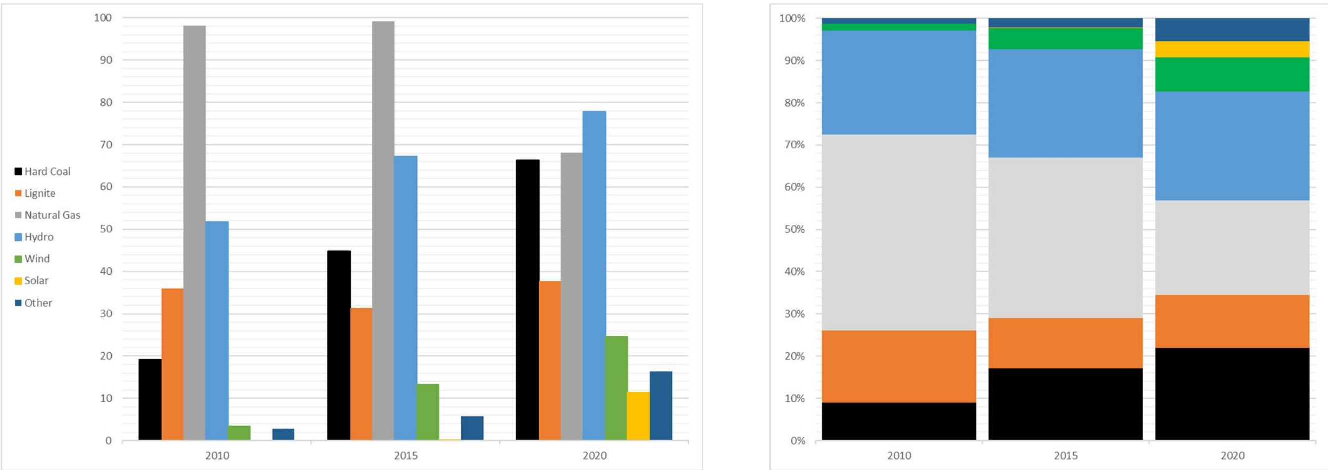
Table 1 summarizes the main economic, energy and environmental indicators for Turkey. The Turkish economy experienced a significant growth in the aftermath of the financial crisis of 2001. The power sector has also shown remarkable expansion, especially in the recent decade, i.e., total generation jumped to 327.16 TWh in 2021 after sticking around 300 TWh in the previous four years. Installed capacity, on the other hand, continued rising in the same period, owing to significant increases in solar PVs and wind turbines (Figure 1). However, the increase in renewables have also been heavily offset by the substantial installations of imported coal plants; thus, only marginal changes have been observed in the path of total emissions.

Figure 2 illustrates the structure of the power sector, both in terms of generations and installed capacities, respectively, for 2018 (the base year of this study). Although its share gradually decreases in the recent decade, natural gas still leads the generation fleet both in terms of installed capacity and generation levels. Besides, fossil-fired (natural gas, hard coal and lignite) plants constitute the top three generation means with two-thirds of the total generation.

[2] Acar and Yeldan (2016) addresses the environmental implications of coal subsidies in Turkey over 2015-2030, and indicates that the economic burden of cutting the subsidies will be negligible (0.5% of GDP) while decreasing, total emissions by %5.

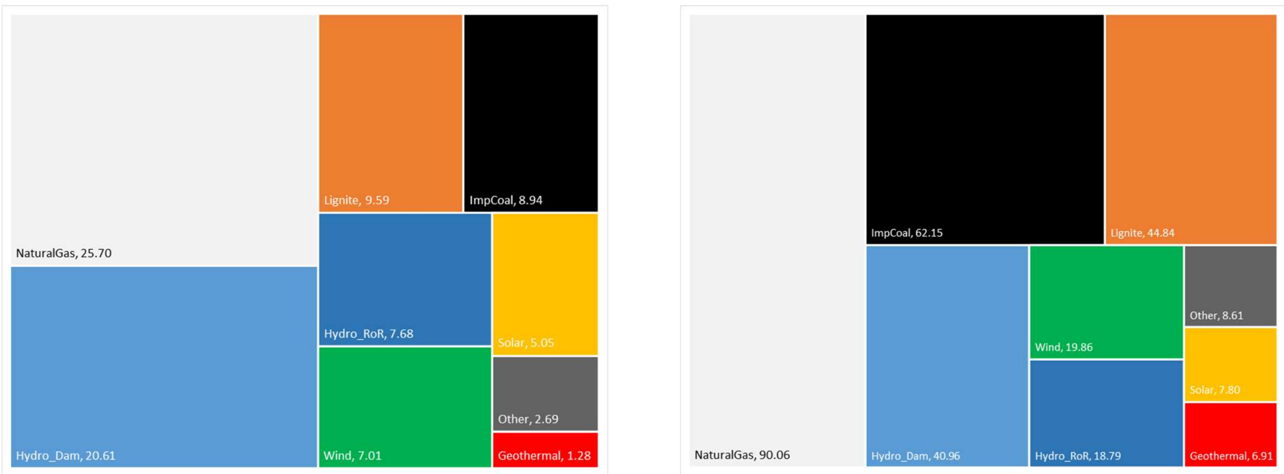
Table 1. Main economic, energy, and environmental indicators for Turkey: 1990-2020.

	1990	2000	2010	2015	2016	2017	2018	2019	2020
Population (million)[3]	56.473	67.804	73.723	78.741	79.815	80.811	82.004	83.155	83.614
GDP (constant 2015 Billion US$)[4]	288.740	413.827	614.171	864.317	893.039	960.034	988.642	997.437	1015.327
Total Primary Energy Supply (Million TOE)[5]	51.44	76.29	105.72	128.81	136.72	146.81	144.20	146.50	147.11
Electricity Generation (TWh)[6]	57.543	124.922	211.208	261.783	274.408	297.278	304.802	303.898	306.703
Electricity Installed Capacity (GW)[4]	16.318	27.264	49.524	73.147	78.497	84.531	88.547	91.256	95.890
CO2 emissions (Mt CO2e)[1]	219.720	299.010	398.676	474.470	500.752	528.312	524.039	508.078	523.897



a) TWh *b) percentage*

Figure 1. Electricity generation by technology: 2010, 2015, 2020. Source: TEİAŞ.



a) Installed capacity by technology: GW. *b) Electricity generation by technology: TWh.*

Figure 2. Power sector in 2018: TEİAŞ.

[3] TurkStat, http://www.tuik.gov.tr/UstMenu.do?metod=kategorist
[4] World Bank, https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=TR
[5] IEA, https://www.iea.org/countries/turkey
[6] MENR of Turkey, Turkish Electricity Transmission Corporation (TEİAŞ), https://ytbsbilgi.teias.gov.tr/ytbsbilgi/frm_istatistikler.jsf

3. Methodology

The main strength of the proposed framework comes from the employment of two BU power models in its structure. This need arises from the wide range of decisions to be made in several dimensions. In other words, power systems comprise both operational and strategic decisions made by different decision makers such as producers, entrepreneurs and regulators. Moreover, there are externalities, e.g., GHG emissions, created by the power sector. MS models provide optimal dispatching and unit commitment decisions under a given generation fleet considering all of the technical and regional parameters precisely under merit order. GEP models, on the other hand, mainly focus on the long-term investment plans that can satisfy the projected demand under technical constraints within the limits of linear or mixed integer linear programming. Instead of renouncing representation features of the two BU models (due to the computational and theoretical restrictions) by forcing them into a single integrated model, it is preferred to keep their fortes as much as possible. This aim was mainly achieved by developing the GEP model in a more realistic structure, i.e., hourly time-resolution, constraints for reserve margins, availability, inter-connection capacities, storage options, emission calculations. Therefore, GEP model is formulated in a way that; in addition to the long-term expansion plan, it can provide a good approximation to power dispatch and unit commitment decisions which establish a base solution for the MS model.

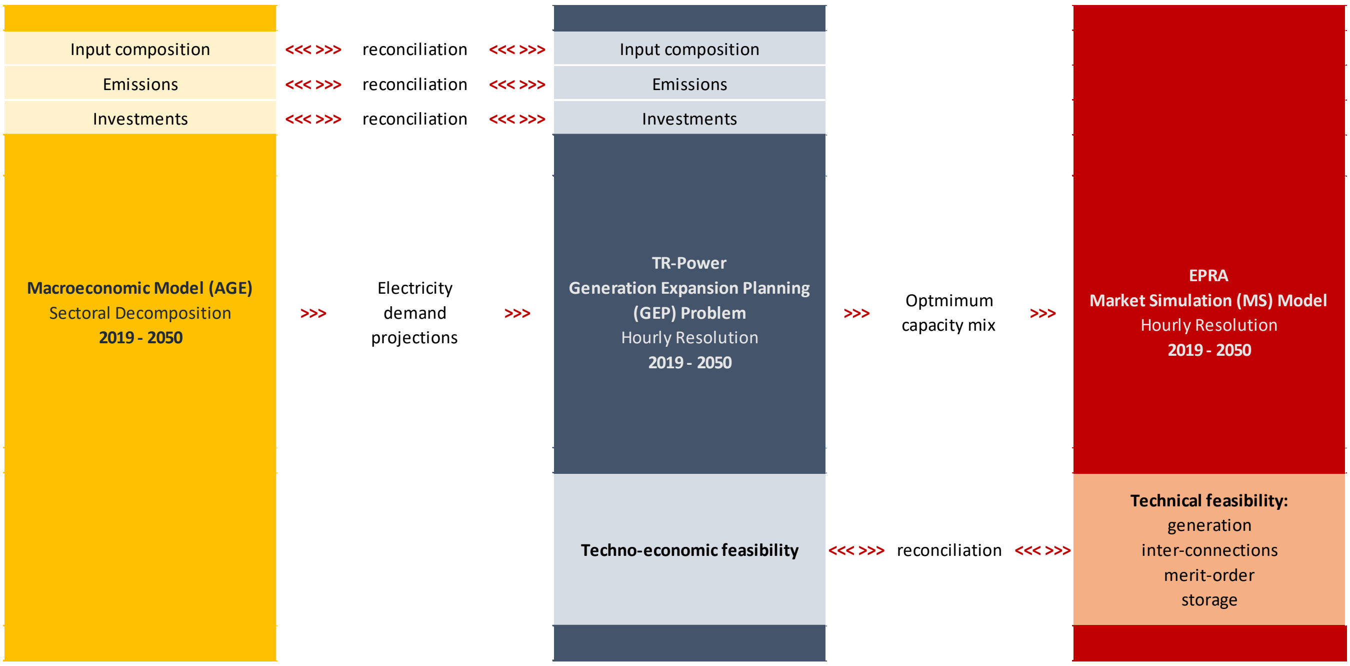


Figure 3. The integrated modeling framework.

The proposed framework is illustrated in Figure 3. As seen in this figure, the GEP model lies in the core of the framework and interacts with both of the model to align all three models. The iterative procedure starts with the solution of the GEP model based on the official electricity demand projections. Next, the solution of the GEP model is transferred to the AGE model with an alignment of several variables including input composition (fuel, capital and labor) in the power sector, emissions and investment requirements. Then, AGE model is re-run to project the revised electricity demand of the economy. The iterations continue until both models consistently converge. On the other hand and concomitantly, each iteration of the GEP model is tested out over each period by the MS model, which utilizes the merit-order dispatch rules. The feedback items from the MS model, e.g., the hours in which the demand is unsatisfied, feasibility of spinning reserves, transmission and inter-connection capacities, base load, export-import balance, etc.; are taken into account by the GEP model and the iterative procedure continues until both of the models are aligned.

3.1. Electricity Market Simulation Model

Market simulation model represents the day-ahead wholesale market in Turkey (i.e., market clearing by ignoring grid constraints). The key inputs, assumptions, and outputs of the market simulations are summarized in Figure 3. Key inputs to the MS model include total power plant capacity by type, merit order of conventional power plants, hourly total demand profile of the grid along the target year (i.e., 2030), and spinning reserve constraints (Cebeci et al., 2019).

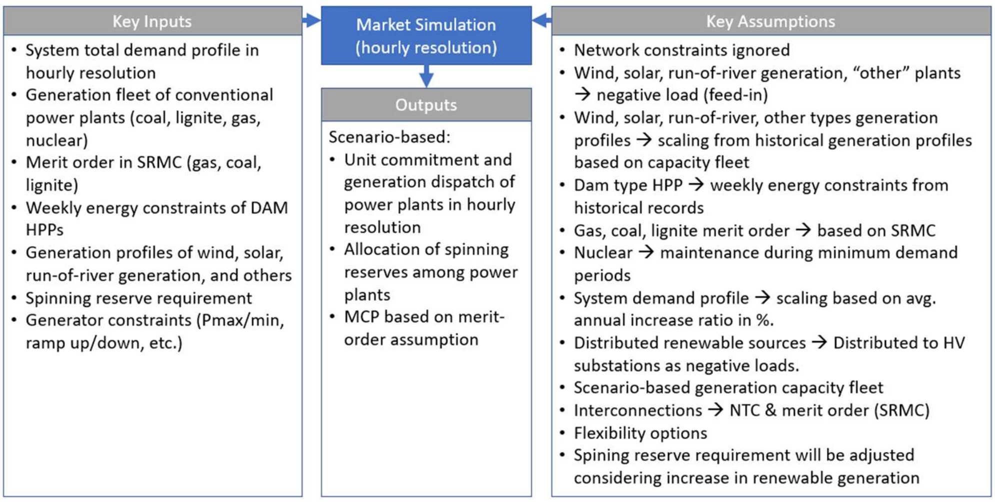


Figure 4. Key inputs, assumptions, and outputs of the market simulation (MS) model

The MS model, in this paper is utilized to test the results of generation expansion planning model under short-term operational constraints, which are presented in Figure 4. Results of market simulation model are then fed back to the GEP model to ensure that the long-term optimal capacity planning is suitable for operational conditions. The two BU models, i.e., the MS model and the GEP model, serve one-another iteratively, until a feasible solution is converged from both long-term and short-term perspectives. Unit commitment of conventional power plants and economic dispatch of committed units are the key outputs of the market simulation model. An example (for an interval of 48 hours) is provided in Figure A1 in the Appendix.

3.2. Generation Expansion Planning Model (TR-Power)

As stated above, GEP models are typically developed to optimally decide on the capacity, technology, location and time of entry into force for the power plants. Technically, these models mostly have an objective of minimizing the sum of (discounted) investment and operational costs over a long-term planning horizon. There is a wide range of GEP models that differ in terms of the mathematical formulation (non-linear, linear, integer, or dynamic programming models), the objective (single or multiple) or the regional scope, (Antunes & Henriques, 2016; Kagiannas et al., 2004; Koltsaklis & Dagoumas, 2018). The GEP model used in this study takes its roots from (Tapia-Ahumada et al., 2015) and is an extended version of TR-Power (Kat, 2021). The significant contributions on top of TR-Power in this study is the integration of energy storage technologies into the power grid and embedding additional backstop technologies (off-shore wind and concentrated solar power - CSP) into the future technology set and defining inter-connection constraints as well as restrictions on net exports.

3.3. Macroeconomic Model

The AGE model is designed top down to be softly integrated with the GEP and the MS models. The model utilizes a consistent macroeconomic/sectoral dataset for Turkey based on GTAP (*Global Trade Analysis Project)* 10 Database (Aguiar et al., 2019) data set to represent 17 production sectors and is calibrated to 2018 macroeconomic general equilibrium of the Turkish economy.[7] This aggregation balances the need to ensure the model is simple and computable against the need to separate key sectors of interest in the results. The industry sectors are further aggregated into High-Energy Intensive and Low-Energy Intensive sectors.

AGE modelling is an applied approach to the Walrasian general equilibrium economic system, comprising behavioral assumptions, production technologies and market institutions together optimizing in response to price signals, all within the resource constraints of general equilibrium. Along with this equilibrium, production processes bring factors of production (capital, labor, and also an energy aggregate input, in our context) within a dynamically adjusting technological pathway. Below, we present an overview of the modeling framework to generate the baseline business-as-usual (BAU) path, in consistency with the assumptions of the baseline BAU paths of the GEP and the MS models.

Production of sectoral output XS_i, is modelled as multi-layer nested structures, which allow one to identify the electricity/energy demand during the production of each sector's output as well as substitution possibilities among the factors/inputs. Here, one way to model the production of (non-electricity sectors) is to assume the materials input (intermediates) to be used in fixed proportion (*Leontief* specification) to the energy-value-added composite,

[7] See Appendix Table A1 for the sectoral aggregation and definitions.

KLE. KLE composite then combines composite energy and value-added (KL) through a *Constant-Elasticity of Substitution* (CES) function. Here, the substitution elasticity between Value Added (VA) and the energy bundle is parametrically given, and assumed to remain constant across sectors. The energy bundle further assumes a second round of substitution between electricity and the non-electric energy (with a (constant) substitution elasticity. Non-electricity primary energy inputs (coal, oil, gas) are finally combined through a CES function. XS_i produced then, is either exported or consumed domestically (See Figure 5 below).

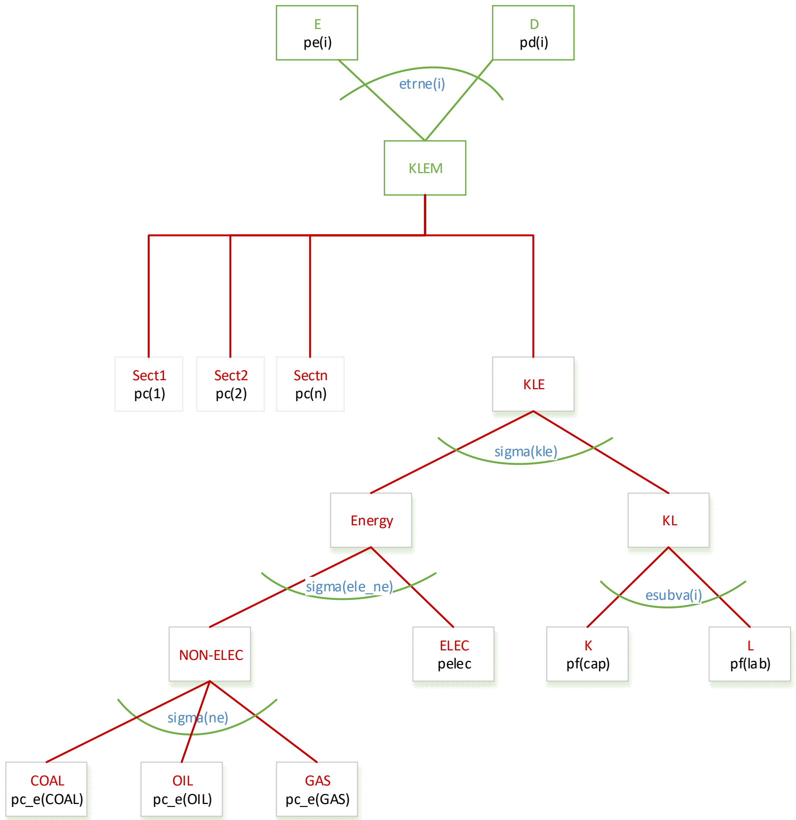


Figure 5. Nesting structure of the production functions.

Incomes are generated, commensurate with the production activities, through the disposition of wages, profits, and other factor payments. Income remunerations are channeled to the households whose role in the system is to dispose-off the generated factor income as (private) consumption expenditures on goods and services or (private) savings. Saving funds, in turn, are disposed-off as investment expenditures on fixed capital to accentuate the potential output in the next production cycle.

Following the identities of national income accounting, any gap on the savings-investment balance domestically is met by foreign savings; that is, the balance on the current account of the balance of payments. Adjustment on a flexible (real) exchange rate (*conversion factor* of the price indexes of the *domestically produced versus foreign* *goods*) or quantity adjustments on foreign exchange flows are possible modes of adjustment to bring forth the warranted equilibrium.

Government, in turn, is institutionalized at every aspect of economic activity considered thus far. Through various administrative capacities of taxation/subsidization, the government acts as both an economic agent fulfilling public expenditure/saving accounts and also as an administrative unit in designing alternative policy scenarios and implementing instruments of abatement.

CO_2 *emissions* of the power sector is embedded into the macroeconomic model, as the macroeconomic modelling framework completely adjust to the output generated by the GEP and the MS models. CO_2 emissions from the rest of the economy are assumed to be the end-result of two sets of economic activities: (1) due to combustion of fossil fuels to produce aggregate energy; (2) due to industrial processes.

Here, emissions from primary energy combustion activities of the production sectors (except for the detailed representation of the emissions from power sector in the GEP model) are set as functions of intermediate inputs of coal, oil and natural gas. Emission coefficients are calibrated, in line with the energy general equilibrium tables of the Ministry of Energy (MoE) which illustrates each sector's energy demand in tons of oil equivalent (toe). The calculated emissions are verified to be consistent with those reported in the GHG emissions inventory published by Turkstat. The emissions from industrial processes are drawn by the volume of production in cement, iron and steel and energy-intensive manufacturing (chemicals). Lastly, emissions from households are set proportional to sectoral consumption of energy inputs.

4. Results

Baseline Macroeconomic Results

In this section, we first describe the main assumptions and characteristics of the 2018-50 pathway under the BAU scenario. Next, we discuss in detail, the feasibility and characteristics of a coal-phase-out (CPO) path, keeping the assumption that the path and sectoral disaggregation of growth under BAU scenario remains largely intact.

The main reference point to construct the BAU scenario is the consistency of the BAU scenarios of the three models. As there are well-defined and well-documented BAU projections for electricity demand in Turkey until 2030 (MENR, 2020), the macroeconomic BAU path produces a baseline that is consistent with the projections of electricity demand and carries the assumptions towards 2050 horizon. Table 2 summaries the major variables along the baseline.

The baseline GDP growth that is consistent with the projections of the electricity demand of the two power-sector models (GEP and MS) and incorporates a modest average rate of growth of energy efficiency (annual growth rate

0.35% b/w 2020-50). The real GDP growth rate along the baseline is 3.7% on average b/w 2020-30; 3.5% b/w 2030-40, 2.9% b/w 2040-50. The electricity demand growth rates are projected to be high, on the order of 4.2% b/w 2021-30 and reduces smoothly thereafter, both by the effect of energy efficiency and the GDP growth dynamics. The CO_2 emissions with an average growth rate around 2.0 percent b/w 2020-50, reach 515 mton in 2030, and 697 mton in 2050.

Table 2. Major macroeconomic variables: BAU.

Year	GDP growth (%)	Real GDP (2018 TRYs)	Electricity Demand - TwH	Elec. Demand growth (%)	Energy efficiency growth (%)
2018		3,724.39	300.00		0.5
2019	0.9	3,758.67	303.90	1.3	0.3
2020	1.4	3,812.31	304.86	0.3	
2023	4.0	4,267.91	353.13	4.0	0.2
2026	4.0	4,805.78	397.46	4.0	0.2
2030	3.8	5,579.85	460.56	3.9	0.4
2035	3.5	6,672.66	539.58	5.9	0.3
2040	3.1	7,824.58	619.46	4.1	0.3
2045	3.0	9,101.56	697.20	2.6	0.4
2050	2.9	10,543.46	769.08	1.4	0.4

The power sector continues to be the single major contributor of the CO_2 emissions under the BaU. Figure 6 below presents the contribution of each sector to total CO_2 emissions (in mtons) along the BaU path. Here, the power sector keeps its leading position throughout the planning horizon with significant increase in magnitude, i.e., over 190 mtons in 2030 and nearly 280 mtons by 2050. Hence, it becomes extremely important to de-carbonize the power sector of the Turkish economy, therefore follow a coal phase-out pathway straightaway. Next section describes this path in detail.

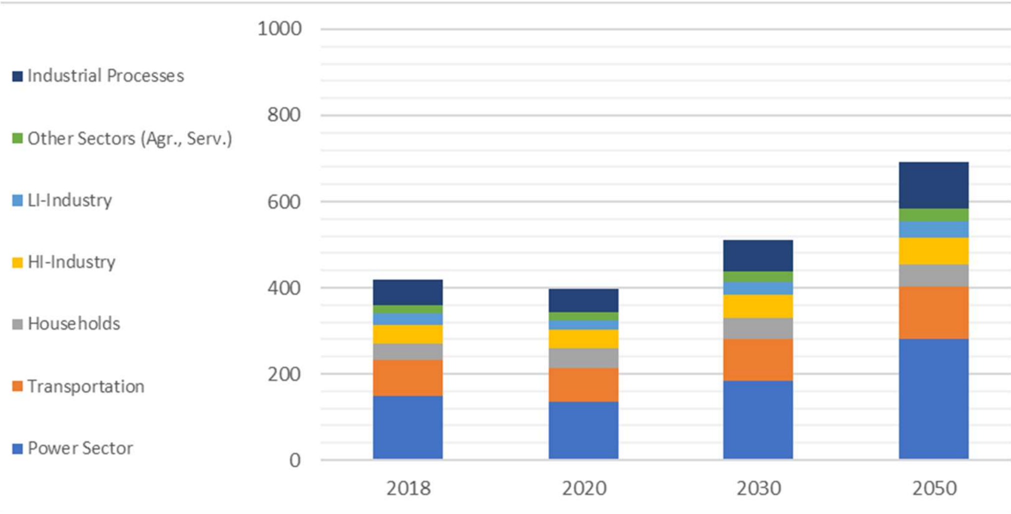


Figure 6. CO_2 Emissions by Sector, BAU (2018-2050)

Coal-Phase Out Results: Power Sector

The generation fleet in the base year (2018) consists of 20.5 GW coal plants which generates 113.4 TWh of electricity. The proposed framework is used to analyze the coal phase-out in the Turkish power sector under two scenarios, i.e., a BAU and a CPO scenario. The scenarios are run over a planning horizon of 2018-2050

The main assumptions of the model and the scenarios can be summarized as follows:

- All cost, technical and environmental parameters are taken from (Kat, 2021).
- Lignite plants are divided into two sub-categories based on the cost and calorific values of the lignite fired in these plants.
- CPO scenario assures that all the coal plants will be closed before 2035. The mere exception is a 1.32 GW imported coal plant officially projected to be active in 2023; this plant is phased-out in 2035.
- Backstop technologies of offshore wind and CSP are introduced in the CPO scenario.
- Mersin Akkuyu nuclear power plant is assumed to be completely (with all four units) commissioned by 2030.
- Generation potentials for solar technology is assigned in hourly basis while monthly assignments are made for wind and hydro resources. These parameters are approximated by the actual values in years 2018-2020.
- Higher upper bounds on penetration levels for solar and wind are defined in the CPO scenario.

Table 3 summarizes the installed capacity and generation amounts under each (BaU and CPO) scenario. Here, total installed capacity rises to 137.3 GW by 2030 and 231.8 GW by 2050 under the BAU scenario. The same figures for the CPO scenario are 158.9 and 360 GWs, respectively. The sharp increase in the installed capacity under the CPO scenario is mainly due to the replacement of coal plants (high capacity factor) with renewable resources (low capacity factors).

Figure 7 explains how a feasible solution would be possible under high shares of intermittent technologies, i.e., solar, CSP, wind and offshore wind. Note that the storage capacity reaches up to 40 GW under CPO while the corresponding value is only 3 GW under BAU by 2050. Moreover, the Cross-border transmission capacity (CBTC) under CPO is 50% more than those under BAU for 2050. Figure 8, on the other hand, illustrates how the phased-out coal power plants are substituted under the CPO scenario. The figure illustrates that coal plants are mainly substituted by solar PVs which are then followed by the wind options and biomass.

Table 3. Installed capacity and electricity generation values under BAU and CPO.

		Biomass	Geothermal	Hydro_Dam	Hydro_RoR	ImpCoal	Lignite	LigniteLow	NaturalGas	Nuclear	Solar	CSP	Wind	WindOS	Other	**Total**
BAU																
Ins. Cap. (GW)	2018	0.8	1.3	20.5	7.8	8.9	5.8	3.8	25.7		5.7		7.5		2.1	**89.9**
	2020	1.1	1.5	23.0	8.2	8.9	5.7	3.8	25.6		6.9		8.6		2.3	**95.6**
	2030	3.0	2.4	23.5	8.2	11.7	6.3	8.7	27.1	4.8	18.9		18.2		4.5	**137.3**
	2040	5.0	3.0	27.5	8.2	11.5	6.3	15.0	32.2	4.8	30.4		42.2		5.7	**191.9**
	2050	4.8	2.8	31.5	8.2	16.7	6.3	15.0	43.2	4.8	44.6		48.0		6.0	**231.8**
Gen. (TWh)	2018	3.0	7.4	42.5	18.8	63.0	32.1	12.6	83.4	0.0	10.7		20.8		5.6	**300.0**
	2020	7.5	10.8	57.8	22.0	56.9	31.1	11.4	62.4	0.0	13.3		23.6		7.9	**304.9**
	2030	20.7	18.1	60.4	20.2	48.4	45.1	41.2	67.1	37.8	37.6		52.1		11.8	**460.6**
	2040	34.5	22.3	72.2	20.6	42.4	45.4	62.2	77.0	37.8	62.8		125.9		16.3	**619.5**
	2050	32.7	21.5	84.3	21.0	66.0	48.1	83.9	111.0	37.8	95.5		148.2		18.9	**769.1**
CPO																
Ins. Cap. (GW)	2018	0.8	1.3	20.5	7.8	8.9	5.8	3.8	25.7		5.7		7.5		1.4	**89.9**
	2020	1.1	1.5	23.0	8.2	8.9	5.7	3.8	25.6		6.9		8.6		1.6	**95.6**
	2030	6.1	3.4	23.5	9.1	4.0	1.7	1.2	33.8	4.8	36.1	0.4	31.9	0.7	2.1	**158.9**
	2040	15.0	3.4	27.5	9.1				36.9	4.8	81.1	2.4	48.0	4.9	2.6	**235.6**
	2050	16.1	5.4	32.0	12.0				32.7	4.8	187.3	5.4	51.6	10.8	2.7	**360.8**
Gen. (TWh)	2018	3.0	7.4	42.5	18.8	63.0	32.1	12.6	83.4	0.0	10.7	0.0	20.8	0.0	5.6	**300.0**
	2020	7.5	10.8	57.8	22.0	56.9	31.1	11.4	62.4	0.0	13.3	0.0	23.6	0.0	7.9	**304.9**
	2030	35.1	22.7	59.2	22.2	14.2	11.2	5.2	97.1	37.8	71.6	1.1	87.2	2.6	5.1	**472.3**
	2040	83.6	21.8	69.4	22.3	0.0	0.0	0.0	68.8	37.8	166.7	7.3	131.4	18.1	4.9	**632.1**
	2050	78.0	28.9	62.8	22.7	0.0	0.0	0.0	37.6	37.8	353.0	9.3	114.4	31.7	4.4	**780.6**

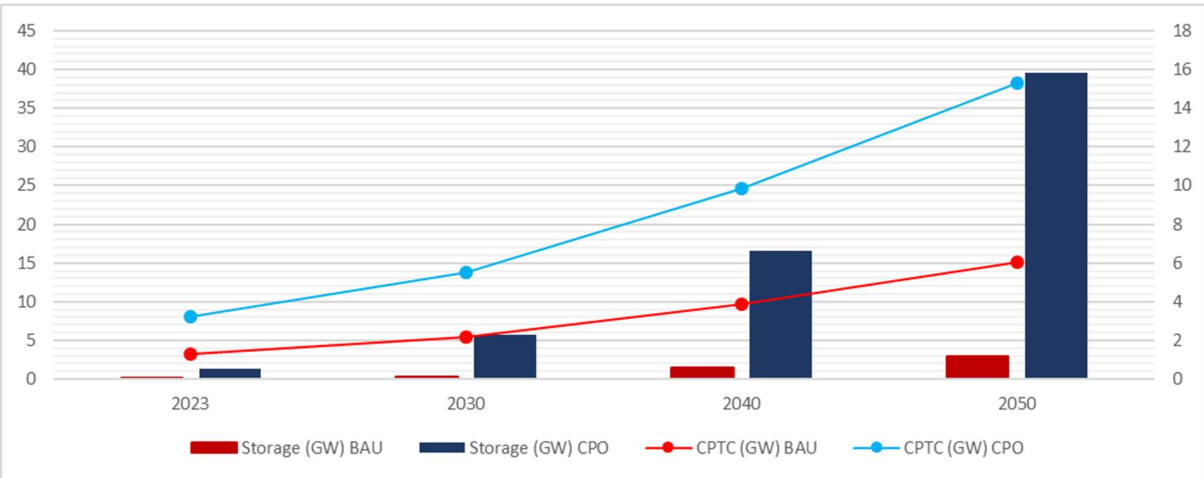


Figure 7. Battery storage (left axis, GW) and CPTC values (right axis, GW): BAU vs CPO.

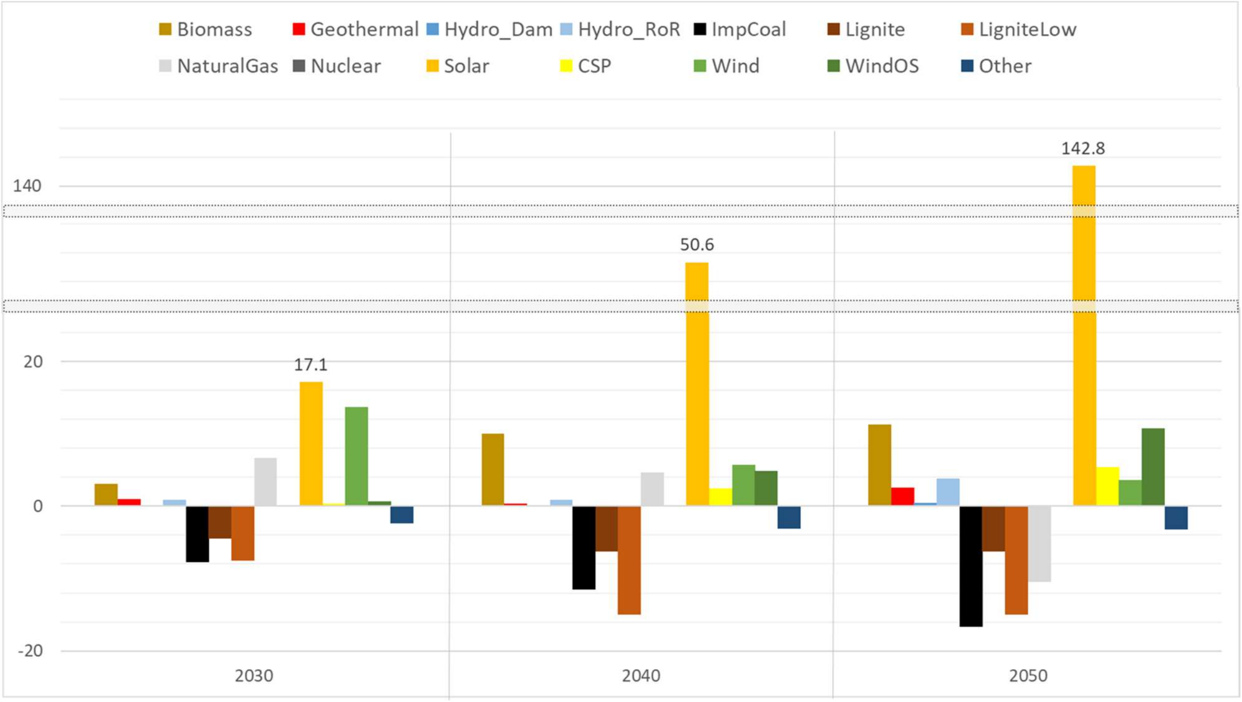
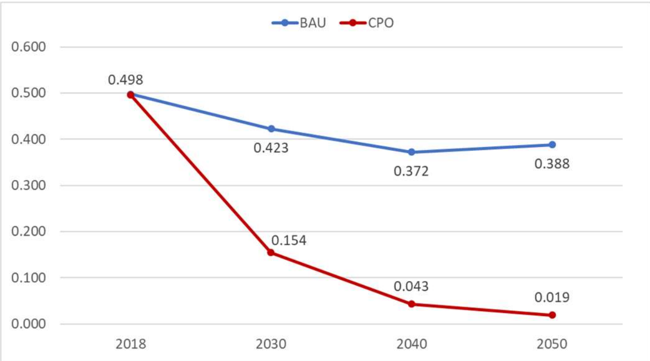
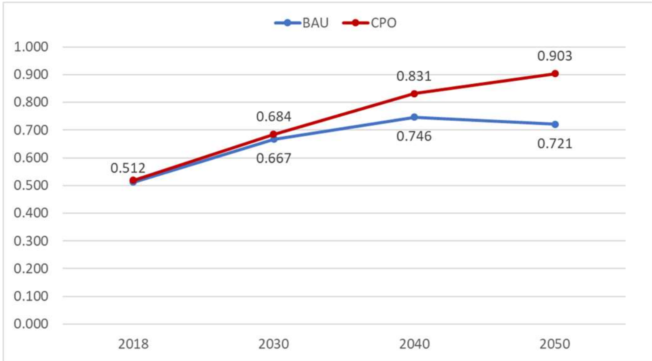


Figure 8. Installed capacity: [CPO-BAU], GW.

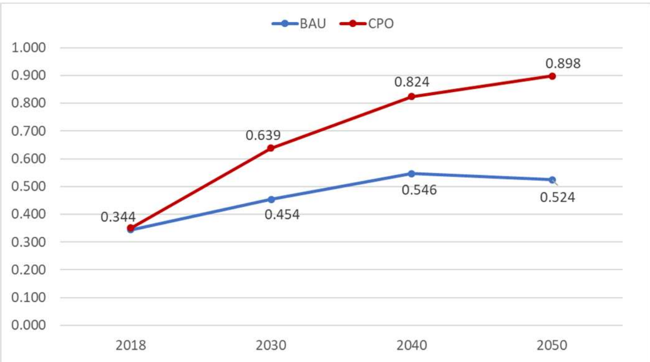
Figure 9 compares the BAU and CPO in terms of the main characteristics of the transition i.e., emission intensity, share of electricity generated by local resources, renewable technologies and intermittent technologies. Here, Figure 9a shows that there is a decreasing trend in the emission intensity (emissions/energy) of the power sector even in the BAU scenario until 2035 (due to official capacity planning for the increased share of renewables). However, the intensity starts to rise after 2040 due to almost full utilization of hydro and wind: besides, the binding constraints on storage and CBTC would not be sufficient to support more generation of intermittent solar power. CPO scenario, on the other hand, points to the possibility of reducing emissions close to zero by 2050. Figure 9b shows that the share of local resources would rise from 51% in 2020 to 90% by 2070 when the imported coal plants are phased out in addition to significant decrease in natural gas. Figure 9c and Figure 9d further present the shares of electricity generated by all renewables and by the intermittent options (solar and wind), respectively. Here, increasing the share of renewables more than half would be hard to satisfy under BAU scenario while an ultimate value of 90% and a remarkable interim value of 64% by 2030 are feasible under CPO scenario. Finally, strict restrictions on storage and CBTC values under BAU can support only 32% of intermittent technology while the corresponding indicator reaches up to 65% under CPO.



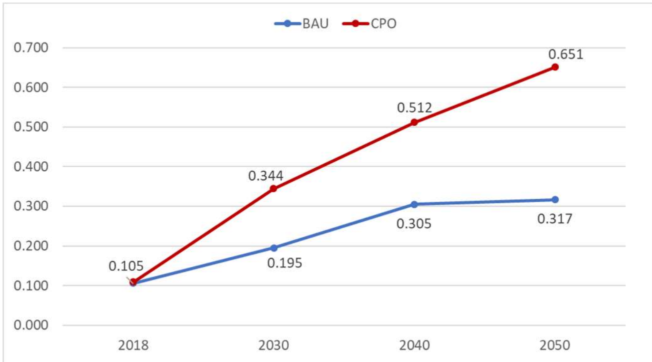
a) Emission intensity (Mt CO_2/TWh)



b) Share of generation by local resources



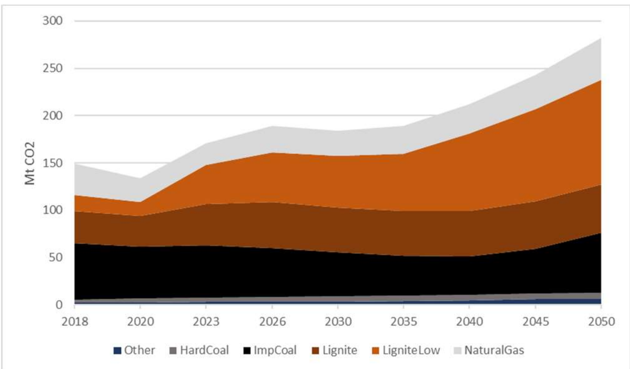
c) Share of generation by renewable technologies



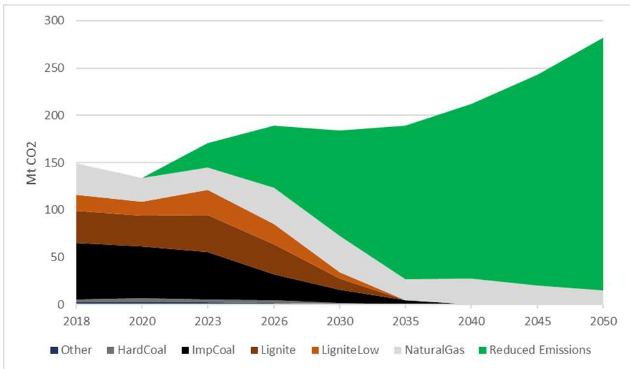
d) Share of generation by wind + solar

Figure 9. Main indicators: BAU vs CPO.

Detailed emissions path of the power sector in Figure 10 illustrates that only the natural gas plants continue to generate emissions after 2035 under CPO and total amount of emission reduction (the green area) sums up to 1.04 Gt CO_2.



a) Emissions by technology: BAU



b) Emissions by technology: CPO

Figure 10. Total emissions in the power sector: BAU vs CPO.

5. *Conclusion and Policy Implications*

Coal phase-out is an integral part of the energy transition strategies related to net-zero emission pathways. Transition from coal to low-carbon alternatives can be considered as low-hanging fruits for carbon-intensive economies. While many countries already follow official coal phase-out pathways in Europe (Europe Beyond Coal, 2022), nearly 50 countries, including the coal majors such as Poland, Germany, Ukraine, and Vietnam, agreed during the COP26 climate conference in Glasgow in 2021, to phase-out coal-fired power plants by the 2040s globally (UKCOP26, 2021). Likewise, phasing out of all unabated coal-fired power plants in 2040 is considered as a stepping stone towards the net zero emissions roadmap for global energy sector of the International Energy Agency (Bouckaert et al., 2021).

Turkey, as a developing country where the highest share of both its electricity generation and power-related emissions comes from coal, will eventually accommodate coal phase-out policies, in harmony with its net-zero emissions target by 2053. On the other hand, any coal phase-out pathway must be compatible with the energy demand and electricity generation system of the country. This study aims a provide an up-to-date and innovative methodology and framework to model Turkey's coal phase-out roadmap. Based on an integrated framework of three different models, this study show that it is feasible to achieve coal-phase out in early 2030s, with 2035 at the latest in Turkey.

IEA suggests that three main issues should be taken into consideration while determining coal phase-out roadmaps: impacts on the local economy, possible price of electricity, and supply security (IEA, 2021b). The integrated model presented in this study evaluates both cost and grid considerations by combining the long-term dynamics consistently with the short-term hourly analysis. Using this model, it is possible to address practical implications of shifting from coal to low-carbon alternatives such as ramp-up ramp-down patterns, power transmission-distribution, base load, and other operational conditions, as well as regional analysis of replacing coal with renewables or gas capacity. Embedding energy storage technologies and interconnection to the integrated model provided an analysis on grid flexibility, which is compromised by higher integration of renewables. The additional backstop technologies (offshore wind and CSP) are also included in the model in order not to be limited only to the leading present-day alternatives.

In conclusion, we argue that although increasing population and energy demand present challenges, phasing out coal-fired power plants is possible within slightly over 10 years thanks to the existing capacity and future potential of renewables in Turkey. Our findings reveal that while real GDP and electricity demand increases over 50%, installed capacity and generation of coal-fired power plants would reduce by 62% and 70%, respectively, between 2018 and 2030, and go down practically to zero in 2035 in our coal phase-out scenario. This shift goes along with expanding installed capacity of wind power by more than 3 times, solar power by more than 5-folds, and total electricity generation of wind and solar by 4-folds until 2030. Consequently, the CO_2 emissions from power sector reduce 50% in 2030 compared to 2018 level.

Admitting a coal phase-out date for the immediate next decade addresses significant policy implications: Calling off new coal power licenses; mapping a phase-out sequence for existing coal power fleet based on age, proximity to the load centers, air pollution, and carbon emissions; and developing legislation, policy tools and market mechanisms to accelerate new renewable installations as well as energy storage technologies and interconnection. On the other hand, scaling up such a transition also requires economic feasibility studies. Here, one should emphasize the culminating literature which provide evidence that climate-friendly investments create more jobs in the renewables sectors than unsustainable investments in the traditional fossil fuel based power sectors (Jaeger et al., 2021). According to Jaeger et al. (2021), for instance, per dollar investment, photo-voltaic solar energy will likely create 1.5 times jobs, and improving the energy efficiency of buildings will be associated with 2.8 times jobs, in comparison to fossil fuel-based investments.

These gains will not be limited only to employment. As (Burrow, 2021) points out, "in developing countries, much of the economy—including the green economy—is informal, with limited access to work security, rights, minimum wages/incomes or social protections"; and the invigoration of renewables-based power generation investments will serve as important catalysts towards mitigating the structural imperfections of the global labor markets. Furthermore, as vehemently documented by IRENA (2019), this transition is also known with its positive gender implications where about 32 per cent of renewable-energy jobs are held by women, in comparison to the 22% share of woman labor employment in oil and gas sectors.

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Appendix

Table A1. Sectoral aggregation and definitions.

Sector Code	Definition	GTAP 2014 Sector Code	NACE REV. 2 Code
agri	Agriculture	1-14	A 1-3
eint	Energy- Intensive Manufacturing: Chemical, rubber, plastic products; Metal products; Metals nec;	33, 36, 37	20-22, 24.4-24.4, 25
othr	Other Manufacturing (Food, Textiles, Wearing App., Motor Vehicles, Electronics, Other Transport Equip.)	19-30, 38-42,	C 10-12
serv	Services	56-58, 62-68	35.2, 35.3, 36, 37, 38, 39, 41, 42, 43, 45, 46, 47, 52, 53, 55, 56, J, K, L, M, N, O, P, Q, R, S, T, U
tran	Transportation	59-61	49-51
ppp	Paper products, publishing	31	17-18
nmm	Non-Metallic Minerals: cement, plaster, lime, gravel, concrete	34	23
otmn	Other Mining: mining of metal ores, uranium, gems. other mining and quarrying	18	07-08
irst	Iron & Steel: basic production and casting	35	24.1-24.3
TnD	Transmission and distribution	43	35.12-35.14
oil	Oil: extraction of crude petroleum and natural gas (part)	16	06.1
gas	Gas: extraction of crude petroleum and natural gas (part); Gas distribution	17, 55	06.2
coal	Coal: mining and agglomeration of hard coal, lignite and peat	15	05
roil	Petroleum, coal products	32	19
NucE	Nuclear Power	44	
RnwE	Renewable Power	47, 48, 50, 52, 54	
FosE	Fossil-fuel Based Power	45, 46, 49, 51, 53	35.11

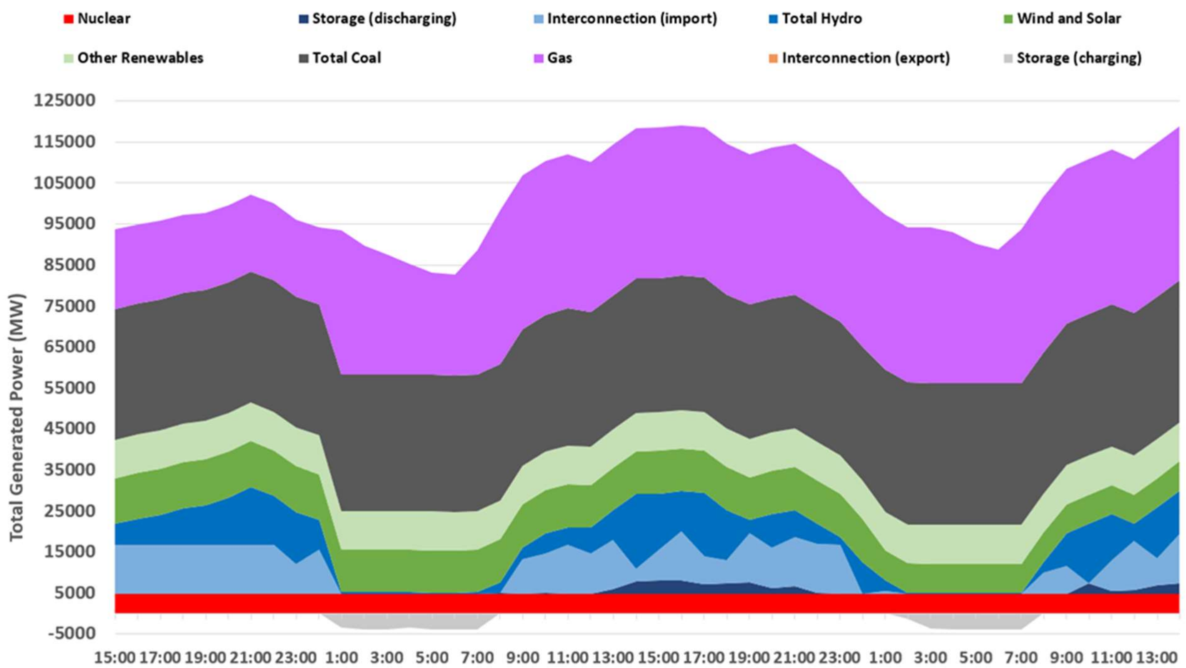

Figure 11. Market simulation model output of a typical day (Baseline Scenario, year 2050).