Renewable energy investment prospects in Turkey's power generation sector

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Abstract: Turkey's power demand is mainly met by fossil fuels. Turkey has recently focused on hydro power development to reduce carbon emissions and fuel imports. However, hydropower efficiency will decrease due to desertification. Turkey's wind power potential is not so high on a national scale. Also, solar farm capacity is almost non-existent though Turkey has a good insolation level. Here, we develop a model that considers various renewable resource options to meet long term demand while maximising the net present value of the power generation sector's investment returns. The results of this model indicate that the sector can be transformed into a sustainable one over the next two decades by directing the majority of new investments to solar power while also using the full potential of wind and hydro power. Renewable resource share can go up to 65% by 2040 and become economical both for the public and private sector.

Keywords: power generation; renewable resources; long term power supply plan; government subsidies; subsidy budget; carbon tax; renewable energy targets; desertification; long term power consumption scenarios; private sector financial planning; net present value; investments; mathematical model; mixed integer programming; Turkey.

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1 Introduction

Energy production is crucial to development, however, power generation processes contribute to GHG emissions significantly. The power generation sector is responsible for about 37% of global anthropogenic GHG emissions (World Nuclear Association, 2017). Both technological and financial measures are adopted by developed and developing countries in order to enable the sector's conversion into a sustainable one. The promotion of electricity generation using renewable resources is a major target in the for sustainable energy production. As a developing country, Turkey has achieved her target of 30% generation share by renewable resource electricity generation plants (REPs), with hydro and wind power having 25% and 7% share, respectively (Ministry of Energy and Natural Resources, 2017). A problematic issue about the focus on hydro power is the desertification of Turkey's south and south-east regions that has led to a significant reduction of hydro energy over the last three decades (Turkish Meteorological Directorate, 2017). Additionally, potential zones for wind farms lie in the Aegean, Marmara and Mediterranean regions where a few locations achieve profitable capacity efficiency. Turkey has not invested on solar energy yet and local PV panel manufacturing capacity is at its infancy. However, with the given insolation levels of certain regions (Renewable Energy Directorate, 2017), Turkey seems to have a great future in solar energy. Turkey's power generation share of non-renewable resource electricity generation plants (NREPs) is currently about 70% and the country imports fossil fuels to meet more than 66% of her annual energy demand (Energy Atlas, 2017). Utilising renewable resources for electricity supply would certainly reduce Turkey's trade deficit, 75% of which is caused by energy imports (Turkish Central Bank Monetary Policy, 2016).

Here, we develop a mathematical model that identifies the optimal locations, capacities and installation dates of new REPs (wind, hydro, solar) to meet Turkish electricity demand during the period 2018–2040. The model maximises the net present value (NPV) of the overall electricity sector so as to provide a roadmap for private investors who wish to embark on energy investments in this country. A scenario of implementing carbon tax on NREPs is considered in the model since Turkey will eventually join other nations that do so. Carbon tax is conceived as a revenue for the government to compensate for REP purchase subsidies. Several scenarios based on different demand levels, different subsidy and carbon tax implementations are proposed to see if the investment strategy is affected for various goals of REP share over time.

2 Literature survey

In the literature, longer term power generation planning models involve two approaches, integer and mixed integer programming and simulation programs. Early surveys covering these studies are found in Baños et al. (2011) and Bazmi and Zahedi (2011) where multi objective models are frequently proposed. In Borges and Antunes (2003), a fuzzy multi-objective linear program is provided with constraints such payments, public deficit limits, production capacity, import and export limits. Objectives include minimising energy imports, carbon dioxide emissions and maximising renewable resource usage. Cormio et al. (2003) propose a network flow model for regional energy planning where REPs and NREPs are suppliers and end users such as agriculture/fishery, transports, industry and residential/commercial sectors are demand points. The goal is to minimise costs. Flores et al. (2014) propose a similar supply chain model that maximises after tax NPV of investments. Gampala et al. (2005) propose a REP/NREP capacity expansion model with transmission network expansion where the objective is to minimise investment and operating costs. San Cristóbal (2012) proposes a goal programming model to solve a location assignment problem for five REPs where the goals are emission savings, investment and operation costs, power demand satisfaction, jobs created, interplant distance and social acceptance. Arnette and Zobel (2012) integrate a mathematical model with Geographical Information Systems to identify most appropriate potential locations for solar and wind farms. Baringo and Conejo (2013) consider wind power investments in a risk-constrained multi-stage stochastic programming model with a multi-stage horizon involving peak demand. Electricity demand, wind power supply and future investment costs are uncertain parameters. Incekara and Ogulata (2017) provide an aggregate generation mix model with a weighted objective that minimises both costs and carbon emissions. Lund and Mathiesen (2009) use EnergyPLAN simulation software with the targets of maintaining energy security, cutting CO_2 emissions and increasing energy exports. Mason et al. (2010) simulate half hourly power demands for a historical time period of 3 years to replace NREPs and maintain lake storage levels. Krajačić et al. (2011) present an energy plan to achieve a 100% REP generation using H2RES model (Duić et al., 2008). A similar model is proposed by Connolly et al. (2011) using EnergyPLAN.

To our knowledge, apart from Incekara and Ogulata (2017), who propose an aggregate energy mix model for Turkey's electricity supply sector, a detailed mathematical model considering investment returns with location specifics has not been presented for Turkey. The feature of maximising private sector's net present value of net profits while considering government subsidy return via carbon taxing is also a novel modelling contribution in this area. The proposed model's flexibility of slowly expanding renewable power supply around same locations also presents an additional practical contribution in terms of investment affordability by the private sector. Furthermore, a unique feature of this model is that the private sector carries out its investments on credit obtained from banks. This feature is specific to Turkish private sector. Our aim here is to provide a guide for optimal locations, types and installed capacities for the private sector during the next two decades.

3 The mathematical model

In the proposed model, we assume that existing NREPs will be gradually replaced by REPs over the planning horizon in order to achieve increasing REP shares. The model is a capacitated facility location/expansion model that determines installed capacities and locations of new REPs over a given planning horizon. Having both binary and float variables, the model is a mixed integer program (MIP). Discrete variables indicate new REP capacity installation, NREP closure, and operational status of the facilities in each period. As a financial model, we assume that private investors acquire initial investment funds for REPs by taking out long term loans currently made available by Turkish banks. The objective function involves maximising the NPV of annual cash flows for new and existing facilities over the planning horizon including loan repayments, investment down payments, operational costs and sales returns for both REPs and NREPs. In the objective function, different levels of carbon tax is deducted from NREP returns according to the mandated scenario. The model incorporates 17 sets of constraints that impose capacity restrictions on both existing and new facilities, enable demand satisfaction andset annual REP share goals. Constraints also calculate facility cash flows and government expenditures for subsidies and government return from collected tax. In the constraints, desertification factor is also accounted for future hydropower output.

The notation used in the model are provided below (all parameters are in CAPITAL letters and all costs and revenues are denominated in USD).

Sets

J set of REP types considered (wind, solar, hydro)

T planning horizon (23 years)

I set of locations of existing and potential power plants

ER set of locations of potential REPs ($ER \subset I$)

FR set of locations of existing NREPs. ($FR \subset I$)

Parameters

FC_j subsidised electricity sales price per MWh of REP energy of type j

EC average market price per MWh of energy

SOC_{ij} operational cost per MWh of REP energy type j (includes fixed and variable operational costs)

B_j number of years to build REP of type j

OC_i operational cost of existing NREP at site i per MWh of energy produced
(α: time value of money

DEP_t	capital discount factor in period t ($DEP_t = (1 + a)^{-t}$)
A_{ij}	{1, 0}: 1 if REP of type j can be built at site i; 0 otherwise
EH_i	hydro power already installed at site i in MW
RVR_i	upper bound on potential installed hydro power at site i in MW
D_t	electricity demand in period t in MWh
AE_{ij}	capacity efficiency coefficient for 1 MW installed power of REP type j at site i
NAE	capacity efficiency coefficient for 1 MW installed power of NREP
INS_i	installed power of existing NREP at site i in MW
RP_t	ratio of REP energy to total energy generated in period t ($RP_t \in [0, 1]$)
CAP_j	amount of initial investment per MW installed power of REP type j
N_j	number of annual payments for a loan ($10 - B_j$)
F_j	annuity payment of REP type j after facility becomes operational, calculated below $$F_j = \frac{\alpha CAP_j}{\left(1-(1+\alpha)^{-N_j}\right)}$$
$NCAP_j$	NPV of the 25% down payment plus all annuity payments over N_j years per MW installed power of REP type j (calculated as follows: $$NCAP_j = \sum_{q=Bj+1}^{10} DEP_q F_q + 0.25 * CAP_j$$
NR_j	NPV of the sales return of 1 MWh of REP energy type j over its lifetime. NR_j is calculated as follows.

$$NR_j = \sum_{q=1}^{10} DEP_q FC_j + \sum_{q=11}^{20} DEP_q EC$$

EHT_0	existing total hydro power generation in MWh at $t = 0$
$EWWT_0$	existing total wind power generation in MWh at $t = 0$
EST_0	existing total solar power generation in MWh at $t = 0$
EW_i	existing installed power of wind farms at site i in MW
WP_i	upper bound on potential wind installed power at site i (in MW) based on available land with appropriate wind speed
TON_i	average GHG emission in tons per MWh electricity generated by existing NREPs at site i
$LOSS_i$	distance-based energy transmission loss percentage at site i (calculated as the weighted average distance from consumption centres with weights reflecting annual demand quantities)

TAX	tax paid per ton of released GHG emissions
DROUGHT	annual reduction percentage of hydro power generation due to desertification (a parameter calculated by applying regression over generated hydropower during the last 25 years)
QUOTA	quota on annual solar power expansion in MW
LOCAL_QUOTA	quota on annual PV solar power expansion in MW at any particular site.

Variables

sp_{ijt}	electricity generated by REP type *j* at site *i* in period *t* (MWh)
y_{ijt}	{1, 0}: 1 if REP of type *j* is operational at site *i* in period *t*, 0 otherwise
ip_{it}	electricity generated by existing NREP at site *i* in period *t* (MWh)
zf_{it}	{1, 0}: 1 if NREP is operational at site *i* in period *t*, 0 otherwise
isp_{ijt}	installed capacity of REP type *j* at site *i* in period *t* (MW)
x_{ijt}	{1, 0}: 1 if REP type *j* is decided to be installed at site *i* in period *t*, 0 otherwise
ir_{ijt}	NPV of initial investment costs for REP type *j* capacity expansion at site *i* in period *t*
tep_t	total power generation in period *t* (MWh)
$netexp_t$	net expenditure balance of MENR: REP energy purchase subsidies minus carbon tax collections in period *t*.
$nret_{ijt}$	NPV of the returns of power generated by REP expansion of type *j* that became operational in period *t*.

The mathematical model is explained below.

In equation (0), we maximise the NPV of the sector’s investments and operations over the planning horizon, assuming that initial investments are made using loans. NREPs are assumed to pay carbon tax. The operational costs and the NPV of loan payments are deducted from new REPs’ sales returns.

$$\begin{aligned}\text{Maximise } Z = &\sum_t \sum_j \sum_{i\in ER} DEP_t * \left[-sp_{ijt} * SOC_{ij} - ir_{ijt}\right] \\ &+ \sum_{j,t} \sum_{i\in BR} DEP_t * nret_{ijt} \\ &+ \sum_t \sum_{ieFR} DEP_t * \left[\left(EC - OC_i - TON_i * TAX\right) ip_{it}\right]\end{aligned} \tag{0}$$

s.t.

In constraints (1), we impose the restrictions that a REP can only be installed at a location once if it is feasible. This constraint does not exclude further expansion after the REP is operational. Installation costs for all expansions are charged in constraints (6).

$$\sum_t x_{ijt} \le A_{ij} \quad \forall j, i \in ER \tag{1}$$

Constraints (2) ensure that a REP of type *j* is operational B_j years after the initial investment decision is made in period *t*.

$$y_{ijt} \le \sum_{q=1}^{t-Bj} x_{ijq} \qquad \forall t, j, \quad \forall i \in ER \tag{2}$$

Constraints (3) ensure that a REP of type *j* is operational in period *t* if it was operational in the previous period.

$$y_{ijt} \le y_{ijt-1} \quad \forall t, j, \quad \forall i \in ER \tag{3}$$

Constraints (4) calculate total power generated in period *t*.

$$\sum_{i \in ER} \sum_{j} sp_{ijt} \frac{1}{(1+LOSS_i)} + \sum_{i \in FR} ip_{it} * \frac{1}{(1+LOSS_i)} = D_t \quad \forall t \tag{4}$$

Constraints (5) ensure that total generated electricity satisfies demand.

$$tep_t = D_t \ \forall t \tag{5}$$

Constraints (6) define the NPV of initial investment costs for REP capacity expansion whose construction started B_j periods ago.

$$ir_{ij,(t-Bj)} - NCAP_j * (isop_{ijt} - isp_{ijt-1}) \quad \forall j, t, \forall i \in ER \tag{6}$$

Constraints (7) define the NPV of sales returns of REP type *j* that became operational in period *t*.

$$nret_{ijt} = AE_{ij} * (isp_{ijt} - isp_{ijt-1}) * NR_j \quad \forall j, t, \quad \forall i \in ER \tag{7}$$

Constraints (8a) and (8b) limit a REP's electricity generation by its installed power multiplied with its capacity efficiency coefficient. Hydro power outputs are adjusted annually according to the drought factor. Equations (8c) link power generation of a REP to its operational status.

$$sp_{ijt} \le AE_{ij} * isp_{ijt} \quad \forall i \in, \forall i \in ER, \forall t \text{ and } j: \text{'solar' and 'wind'} \tag{8a}$$

$$sp_{ijt} \le (1 - t * DROUGHT) * AE_{ij} * ISP_{ijt} \quad \forall i \in ER, \forall t \text{ and } j: \text{'hydro'} \tag{8b}$$

$$sp_{ijt} \le BIGM * y_{ijt} \quad \forall i \in ER, \forall t, j \tag{8c}$$

Constraints (9) limit electricity generation of existing NREPs by their installed power if they are still operational in period *t*.

$$ip_{it} \le NAE * INS_i * zf_{it} \quad \forall i \in FR, \forall t \tag{9}$$

Constraints (10) decide on the operational status of the NREP at site *i*. A plant is operational if it has not closed down in the last period.

$$z_{fit} =\le \sum_{q=1}^{t-1} zf_{iq} - \sum_{q=1}^{t-2} zf_{iq} \quad \forall i \in FR, \forall t \tag{10}$$

Constraints (11) set a goal for the ratio of REP generation to total electricity generation in period *t*. Different values of RP_t are assigned in different periods, gradually raising the share of REP energy.

$$EST_0 + (1 - t * DROUGHT) * EHT_0 + EWWT_0 + \sum_{i \in ER} \sum_j sp_{ijt} \geq RP_t * tep_t \quad \forall t \tag{11}$$

Constraints (12) impose an upper bound on the installed power of hydro plants on a given river i based on the river's maximum potential.

$$sp_{ijt} \leq RVR_i - EH_i \quad \forall i, \forall t \text{ and } j: \text{'hydro'} \tag{12}$$

Constraints (13) impose a site-based limit on wind power installation calculated using windy acreage available at the site.

$$sp_{ijt} \leq WP_i - EW_i \quad \forall t, \forall i \in ER, \text{ and } j: \text{'wind'} \tag{13}$$

Constraints (14) impose an annual quota on solar installed power expansion. Constraints (15) impose the same restriction at a local level to distribute solar installed power among different sites for equally distributed employment means.

$$\sum_{i \in ER} isp_{ijt} \leq \sum_{i \in ER} isp_{ijt-1} + QUOTA \quad \forall t, \text{ and } j: \text{'solar'} \tag{14}$$

$$isp_{ijt} \leq isp_{ijt-1} + LOCAL\_QUOTA \quad \forall i \in ER, t, \text{ and } j: \text{'solar'} \tag{15}$$

Equation (16) define MENR's net balance calculated as total REP purchase expenses minus NREP carbon tax collection.

$$netexp_t = \sum_j \sum_{i \in ER} \left(FC_j - EC\right) * sp_{ijt} - \sum_{i \in FR} TON_i * TAX * ip_{it} \quad \forall t \tag{16}$$

Constraints (17) define variable domains.

$$x_{ijt}, y_{ijt}, zf_{it}: \{1, 0\} \text{ and discrete } sp_{ijt}, ip_{it}, isp_{ijt}, ir_{ijt}, nret_{ijt}, tep_t \geq 0. \text{ Free } netexp_t \tag{17}$$

4 Design of experiments

We run the model for six scenarios where future demand varies in the interval [–20%, 25%] over expected demand. In Table 1, we present the changing scenario parameters.

Table 1 Summary of scenarios

Parameter	*Scenarios*					
	1	*2*	*3*	*4*	*5*	*6*
% over centreline demand	+10	+10	+10	–20	–20	+25
Renewable goal in 2030	35%	35%	50%	50%	50%	30%
Renewable goal in 2040	50%	50%	65%	90%	90%	50%
Carbon tax (\$/ton CO_2)	0	30	30	30	25	30
Purchase price (\$/MWh) wind, solar, hydro	73, 133, 73	80, 120, 80	73, 120, 73	73, 120, 73	73, 133, 73	73, 120, 73

The annual power demand presents an uncertainty in long term planning. We obtain a regression equation with the centreline given by $D_t = 0.3051t^2 + 1.5079t + 73.375$ with a R^2 value of 0.9714 using past annual consumption data. The first three scenarios have a demand parameter 10% above the centreline, whereas the last scenario's demand is 25% above the centreline assuming better than expected economic growth. The 4th and 5th scenarios have annual demands that are below 20% of the centreline, considering a possible natural disaster effect on consumption in Marmara region. Other parameters that vary over scenarios are the annual renewable resource usage goals in power supply that gradually increase over time until the year 2030 and the year 2040. We also vary the carbon tax per ton CO_2 emissions. A tax rate of $30/ton deters new investment on coal plants. The break-even tax level for new coal plant investments is $26/ton. For a new coal plant, a tax level of $25/ton results in a net profit margin of 23% during its lifetime whereas new fuel oil and natural gas plants would be much more profitable due to their lower CO_2 emissions. In the 5th scenario, we reduce both the carbon tax and the free market electricity purchase price to check if more NREP closures occur. The last parameters that change over scenarios are the subsidised power purchase prices by the government for REPs that are less than 11 years old. In the 1st and 2nd scenarios, the purchase prices are the currently valid ones as of 2017. We change these prices in order to calculate their impact on the government's subsidy expenses over the planning horizon.

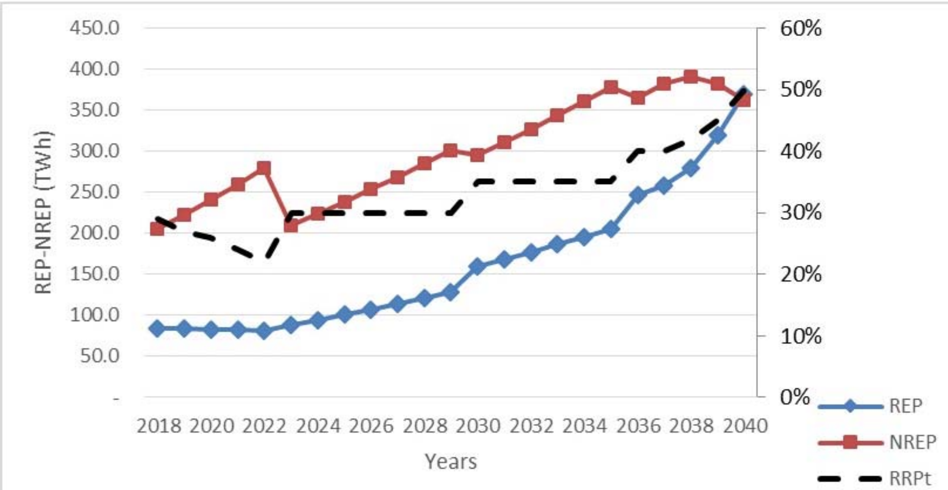
5 Results and conclusions

Each scenario is solved by the commercial IBM ILOG CPLEX solver version 24.4.3 released in 2015. In all scenarios, we observe that a slowly increasing REP generation growth takes place thanks to solar capacity expansion. For instance, in scenario #1, Figure 1 depicts the rise in REP/NREP energy generation (in TWh) in accordance with the imposed renewable resource share goals over time. We notice that NREP power generation suddenly drops in 2022 due to the entry of nuclear energy. Up to 2022, RRP_t diminishes due to increasing demand, then, supported by nuclear and solar power, it rises up to 50% by 2040. This is a typical behaviour for all scenarios. In all scenarios, the model introduces hydro and wind power capacity expansions at their full potentials during the last years of the planning horizon which correspond to 12% of the required supply.

Table 2 NREP capacity usage

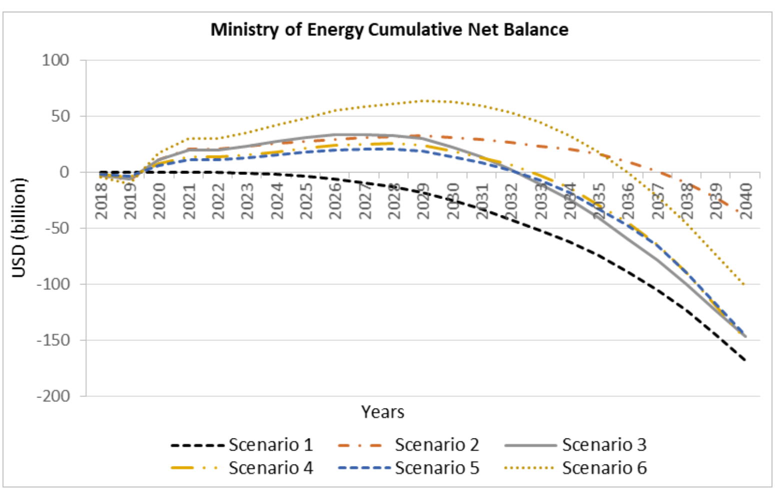
Year	*% NREP capacity usage in scenarios*				
	1	*2*	*3*	*4 and 5*	*6*
2030	75	70	58	46	100
2040	98	93	65	15	100

Figure 1 REP and NREP power generation over time in TWh and the share of renewable resources (RRP_t) in scenario #1 (see online version for colours)



In Table 2, we observe NREP facility capacity usage percentages in all scenarios in the years 2030 and 2040. The first two scenarios' NREP capacity usages are similar at 75%/70% and 98%/93% in 2030 and 2040, respectively. Scenario #3 reduces these numbers to 58% and 65%, while scenarios #4 and #5 further reduce NREP capacity usage to 46% and 15%, however, in the optimistic scenario all NREP capacity is used from 2030 onwards due to high demand and solar power quota limitations.

Figure 2 Net spending (subsidy-tax) of the ministry of energy in all scenarios (see online version for colours)



In Figure 2, we illustrate the annual cumulative net balance of the Ministry of Energy (tax collected-subsidised purchase expenses). In scenario #1, MENR starts spending money on subsidies starting from 2023 onwards, and its balance is always in the negative domain, because no carbon tax is implemented. A total of $168 billion has to be spent to achieve a 50% REP share in total power generation by 2040 and the annual expense is $23.3 billion in 2040. In scenario #2 where tax is implemented, MENR collects more cash than it spends until 2038 and ends up spending $15 billion in 2040 with cumulative net expenditures reaching only $38 billion by the end of 2040. Scenario #2 seems financially achievable. The same observation is valid in the optimistic scenario #6, though net balance becomes negative earlier in 2037. In 2040, MENR's net annual balance is –$27.7 billion in scenario #6, but its cumulative net expenditure is at $101 billion despite tax collection and lower REP purchase prices than in scenario #1. Despite its more ambitious REP energy share, scenario #3's cumulative net expense by 2040 is lower than that of scenario # 1 at $148 billion due to lower subsidies and tax collected. Scenarios #4 and #5 also have similar cumulative expenditures despite the drop in demand, because a higher REP energy share is achieved.

Table 3 Sector NPV and dissected NPVs (in billion USD)

	Scenarios					
	1	*2*	*3*	*4*	*5*	*6*
Sector NPV	249.621	178.448	140.624	128.779	97.236	174.299
NPV wind	6.712	6.712	5.053	5.053	3.794	6.215
NPV solar	98.233	98.208	66.241	69.308	51.333	91.424
NPV hydro	6.007	6.007	3.144	3.144	2.369	3.860
NPV NREP	138.669	67.520	66.186	51.274	39.740	72.801

In Table 3, we dissect the objective function into four parts, and present the NPVs of renewable resource investments of three types and the NPV of NREP operations across all scenarios in billion USD. Major investment lies in solar power, therefore this REP type is the largest contributor to the sector's returns. NREP returns make up the majority of the energy sector's returns in scenario #1 where no tax is implemented. In all other scenarios, tax implementation and higher shares of REP generation result in lower NREP returns.

Analysis of the results indicates that the path for clean energy lies on establishing solar farms on a fast track. Turkey has a large land area and even the most ambitious plan ends up using less than 1% of her acreage. The Ministry can hasten the pace of progress or slow it down depending on its future annual budgets and tax collection policy from NREPs.

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