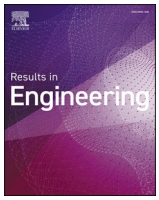
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Assessment and determination of 2030 onshore wind and solar PV energy targets of Türkiye considering several investment and cost scenarios

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ABSTRACT

The importance of renewable energy (RE) shift increases as the instabilities around the world enhanced by the pandemic raise issues about energy security while the energy demand of countries continue to increase. This is especially the case for Türkiye, which is a member of OECD and among developing countries. In the next decade, onshore wind, and solar photovoltaics (PV) will be the focus of Türkiye's RE sector due to the rapid decrease in their costs. Hence, reasonable estimation of investments to the RE sector and cost projections of onshore wind and solar PV is crucial to plan, decide and set effective energy policies. In this study, three different investment scenarios are generated for RE of Türkiye. In addition, global and local cost projections are conducted for onshore wind and solar PV, again in three different scenarios. These scenarios are then utilized to estimate the annual installed capacity changes of Türkiye. Then, annual installed capacity amounts of Türkiye for onshore wind and solar PV are projected until 2030 in five novel scenarios: Economic, Average, Ambitious, Best-Case, and Worst-Case. According to the results, achievable and the most suitable 2030 targets for onshore wind and solar PV are determined as 25,000 MW and 60,000 MW for Türkiye, respectively. These results will assist the policymakers by elucidating the onshore wind and solar PV future of Türkiye, and the methodology may be useful for determination of RE targets for other countries.

1. Introduction

Energy generation has always been a crucial priority for nations worldwide for both economic and security concerns [1,2]. This is especially the case in 2022, where instabilities around the world enhanced by the COVID-19 pandemic threaten the supply of energy [3] while the energy demand continues to increase [4]. In addition, the world faces a climate emergency which necessities the utilization of the renewable and clean sources rather than the fossil fuels in energy generation [5,6]. The International Energy Agency (IEA) repeatedly reports that the temperature rise cannot be kept bellow 2 °C if additional fossil fuel projects are realized [7,8]. It was emphasized that the "net-zero" hinges on an unprecedented clean technology push to 2030 [7]. In addition, in terms of both sustainable development goals (SDG) 7 (affordable and clean energy) and 13 (climate action), the transition from fossil based energy to the renewable energy is crucial. Indeed, renewable energy transition has been counted as one of the most promising approaches for meeting the world's increasing energy demand [9]. Hence, reasonable assessment and determination of annual and overall renewable energy targets up to 2030 has gained immense importance.

To begin the discussion on the costs of renewable energy technologies, two main indicators should be introduced: the total installed cost (TIC) and the levelized cost of electricity (LCOE). The TIC is used to indicate the cost of energy capacity (usually in USD/kW), while the LCOE is used to indicate the cost of electricity production (usually in USD/kWh) [10–12]. These two indicators are related in solar and wind energy technologies since the operating costs (opex) is much lower than initial investments (capex) [13]. LCOE is a useful tool to evaluate the performance of individual projects over time, while TIC is generally used for macro-economic analysis since it directly relates the energy capacity and the capex.

Among renewable energy technologies, onshore wind and solar PV have recently reached grid parity and have become economically competitive with the other energy sources [14]. Global projections of Sens et al. shows that the capex of onshore wind and solar PV

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Table 1
Data collected for evaluations and projections [29].

Data Type	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Türkiye's Wind Capacity (MW)	1729	2261	2760	3630	4503	5751	6516	7005	7591	8832
Türkiye's Solar Capacity (MW)	7	12	19	41	250	834	3422	5064	5996	6668
Türkiye's Wind TIC (2020 USD/kW)	2264	1792	1976	1909	1966	1982	1789	1897	1703	1347
Türkiye's Solar TIC (2020 USD/kW)	N/A	N/A	N/A	N/A	N/A	1585	1271	1220	932	827
Global Wind TIC (2020 USD/kW)	1939	1995	1851	1797	1659	1652	1647	1566	1491	1355
Global Solar TIC (2020 USD/kW)	4007	3021	2647	2393	1823	1657	1432	1223	1009	883

Table 2
Calculated investments in comparison with the total public finance flows retrieved from IRENA. * [29].

Year	Calculated Onshore Wind Investments (Million $)	Calculated Solar Investments (Million $)	Calculated Total Investments (Million $)	IRENA Türkiye's Total Public Finance Flow* (Million $)
2011	1204.7	0.0	1204.7	801.71
2012	894.4	0.0	894.4	280.19
2013	1719.5	0.0	1719.5	595.99
2014	1666.3	0.0	1666.3	533.85
2015	2453.5	0.0	2453.5	430.44
2016	1516.4	4102.5	5618.9	1460.23
2017	874.8	2087.7	2962.6	403.6
2018	1111.8	1137.2	2249.0	1098.02
2019	2113.2	626.4	2739.6	360.12

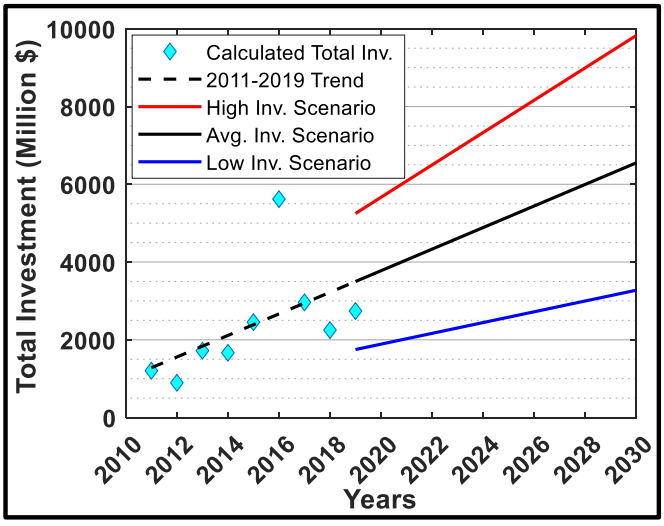


Fig. 1. The high, average, and low investment scenarios for Türkiye.

technologies will decrease around 13% and 50%, respectively between 2020 and 2030 [15]. Ling-zhi et al. expects around overall 60% decrease in solar PV costs in different regions of China for the same period [16]. IRENA expects around 30% decrease in the costs of onshore wind technologies between 2018 and 2030 in their global analysis [17]. An expert elicitation survey reported by Wiser et al. predicts 37%–49% decrease in wind energy costs by 2050 [18]. It should also be noted that COVID-19 had a minor impact on solar and wind energy sector and rapid recovery is expected in the following years [19,20], and the investment and cost trends are unlikely to be affected for annual analysis.

Numerous LCOE and TIC projections up to 2030 and 2050 are conducted for onshore wind and solar PV energy technologies. These projections are updated continuously in the light of new economic data and technological developments. Many studies use multivariate analysis to estimate the LCOE or TIC as a function of many variables for the most accurate predictions [15,21]. However, the complexity of the obtained models also increase, and the applications of such projections become challenging in a macro-economic perspective where retrieving some necessary information may be difficult or even impossible. Hence, in this study, we constructed elementary models by modified regression approach for solar and wind energy, which are adequate for the scope of this study, and in-line with the literature.

Türkiye is among developing countries and an OECD member, located between Europe, Asia, and Africa [22]. The electricity demand of Türkiye increases at a faster rate than the world average (%5 per year, compared to %3 per year between 2000 and 2019) [23]. However, Türkiye can only provide 56.4% of its energy demand in 2020 [24], which makes the country highly depended on the energy imports and raises economical and security issues. Thus, for sustainable development, Türkiye needs to plan its energy future by determining effective targets. As of 2020, the total installed capacity of Türkiye has reached 95,890 MW. The share of renewables is 53.4% in terms of installed capacity [24]. While the hydropower energy makes up the larger part of the installed capacity of renewable energies (around 60%), the economical projects have already been installed and the hydropower installed capacity is not likely to increase in the following years [25,26]. However, the onshore wind and solar photovoltaic (PV) technologies have just reached the grid parity, meaning that the wind and solar energy projects are now economically competitive with the other energy sources including hydropower and fossil fuels [14]. Thus, the installed capacity increases will mostly result from the developments of solar and wind energy in the following decades. In a recent study, Erat et al. reports that Türkiye's installed wind and solar capacities will reach 25,000 MW and 38,000 MW in 2030, respectively [27]. However, Shura reports that under current policy scenario, the onshore wind and solar PV capacities will only reach 16,679 MW and 19,796 MW in 2030, respectively [28]. Other scenarios predict that these capacities may be increased up to 32,224 MW for onshore wind and 41,339 MW for solar PV by 2030 [28], which is in-line with the results of the former studies. It should be noted that, as far as we know, Türkiye has not yet announced official targets for 2030, and this study aims to assist the policymakers in determination of these targets.

In this study, the wind and solar energy futures of Türkiye are analyzed in detail from a macro-economic perspective. Firstly, three different investment scenarios for Türkiye are determined. Then, TIC projections are conducted for solar and wind energy, again in terms of three different cost scenarios. Dividing the projected investment amounts by the projected TICs and then taking the annual difference, the yearly installed capacity changes are obtained. These installed capacity changes show what would happen if all the investments are channeled to the wind or solar energy sectors, respectively. Finally, the projections of economic, average, ambitious, best-case, and worst-case scenarios for Türkiye are conducted, illustrated, and discussed in detail. The novelty of this study can be summarized as follows:

- A straightforward methodology for determination of wind and solar energy targets is explained for the first time in the literature, which may than be utilized for different countries and different energy sources
- Global and local cost projections are carried out for wind and solar energy with the most up-to-date data in the literature

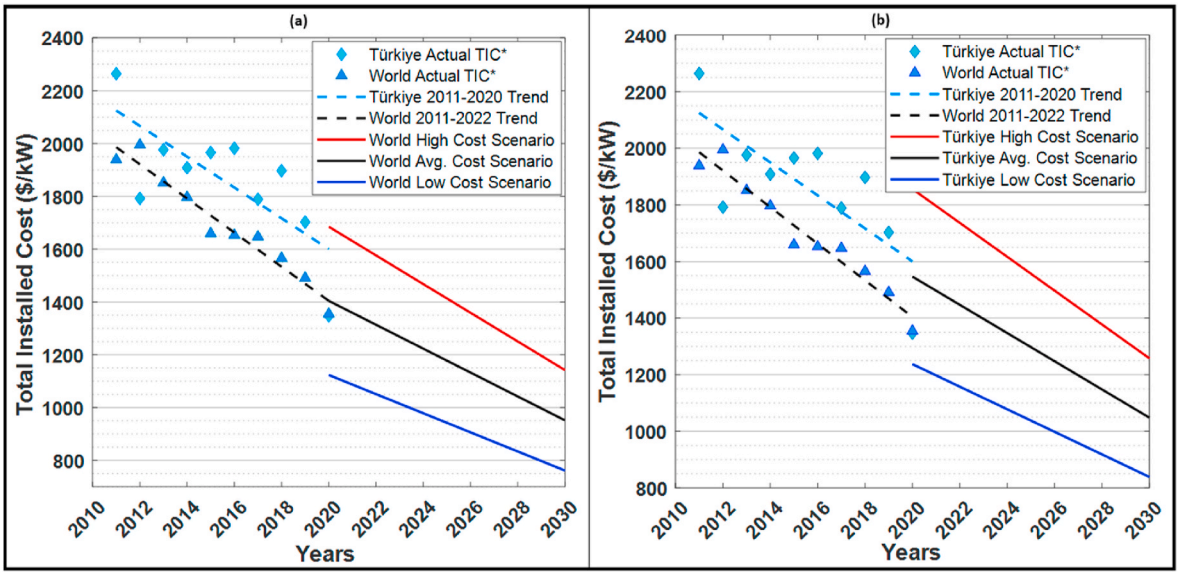


Fig. 2. Global (a) and Türkiye's (b) TIC projections of onshore wind for different scenarios until 2030. * [29].

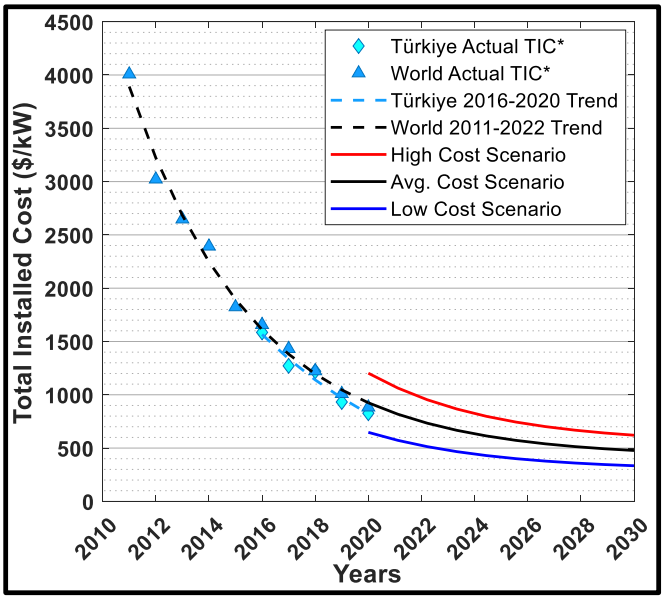


Fig. 3. Global and Türkiye's TIC projections of solar PV for different scenarios until 2030. * [29].

- Finally, annual, and overall wind and solar energy targets for Türkiye has been assessed and determined until 2030 based on novel scenarios.

Consequently, the results of this study provide critical insights on using TIC and installed capacity for assessment of future energy targets and shade light on the future of Türkiye's onshore wind and solar PV energy sector until 2030 while providing several options for the policymakers.

This paper is structured as follows. In section 2, the methodology of the data obtainment, cost projections, and the installed capacity projections for Türkiye is explained in detail. In section 3, the results of the projections are presented, discussed, and compared with the literature. The paper ends with conclusions in section 4.

2. Methodology

2.1. Data

The data utilized in this study was obtained from the latest renewable statistics report of IRENA [29]. Table 1 shows all the collected data to be used for illustrations, evaluations, or projections conducted in this study. Here, the onshore wind and solar PV installed capacities and TICs are used for the generation of investment scenarios, the TIC data is used for the obtainment of global and local TIC projections. Then, the installed capacity projections are conducted by evaluating the annual capacity changes which are evaluated by the former analysis.

2.2. Scenario generation

There are numerous unpredictable factors in estimating the available funds to be used for solar PV and onshore wind, and the costs of the renewable energy technologies [30]. To overcome this challenge, two main approaches are observed in the literature. One is the multivariate modeling of the desired output (cost or investment amount) in a detailed fashion with several assumptions [13,15,21]. While this approach may be preferable in estimation of costs of individual projects, the multivariate nature of the models can make them inconvenient for their utilization in macro-economic analysis. In addition, Xiao et al. reports that several projections conducted in this manner has underestimated the decrease in the costs of renewable energy sector [31]. The other one is constructing several models for different scenarios to contain the uncertainties in the bounds of the projections [28]. This approach provides the researchers and policymakers with the ability of assessing the study continuously and choosing the most appropriate scenarios according to their own knowledge about the industry. The latter approach was adopted for this study, and investment and cost scenarios are generated as explained in the following sections.

2.2.1. Investment scenario generation

By multiplying the annual difference of installed capacity and TIC values for Türkiye (see Table 1), annual investment amounts are determined for both onshore wind and solar PV energy according to Eq. (1). Then these values are summed up to evaluate the annual investments between 2011 and 2020 to the onshore wind and solar PV sector, combined. This data is used for forecasting the investment amounts in three different scenarios. To obtain the average scenario

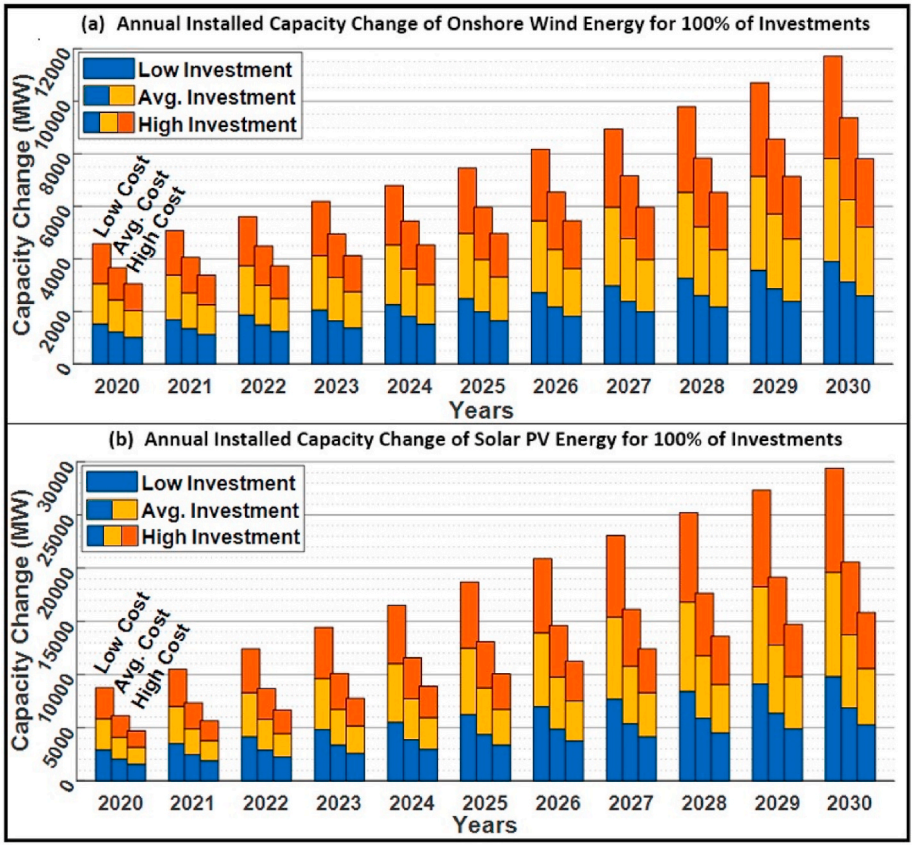


Fig. 4. Evaluated annual installed capacity changes of onshore wind (a) and solar PV (b) for all scenarios.

Table 3
Annual capacity changes in 2020 and 2030 for onshore wind and solar PV for all constructed scenarios and different investment distributions.

Scenarios	Annual Capacity Changes (In 2020 – In 2030) (MW)					
	Onshore Wind			Solar PV		
	100% Inv.	50% Inv.	30% Inv.	100% Inv.	50% Inv.	70% Inv.
Economic	1220–3120	610–1560	370–940	2040–6860	1020–3430	1430–4800
Average	2450–6250	1230–3130	740–1880	4080–13,720	2040–6860	2860–9600
Ambitious	3660–9370	1830–4690	1100–2810	6130–20,580	3065–10,290	4290–14,410
Best Case	4580–11,720	2290–5860	1370–3520	8750–29,410	4375–14,710	6130–20,590
Worst Case	1020–2600	510–1300	310–780	1580–5280	790–2640	1110–3700

model, linear regression is applied on the finance flow data to obtain the trend of the capex with respect to the years. Here, the dependent variable is the annual total investment and the independent variable is the years. Then, for low and high investment scenarios, which are determined to be the ±50% of the average cost scenario, the obtained equation is multiplied by 0.5 and 1.5, respectively.

$$Inv(t) = TIC(t) \bullet (Cap(t+1) - Cap(t)) \quad (1)$$

where $Inv(t)$ is the investment amount at the year t, $Cap(t)$ is the installed capacity at the year t, and $TIC(t)$ is the TIC at the year t.

2.2.2. Cost projection scenario generation

The yearly TIC data between 2011 and 2020 given in Table 1 is used for conducting the cost projections.

For onshore wind, a linearly decreasing trend was observed both for Türkiye and the world. However, when linear regression is applied on the global data, it is observed that the costs are illogically low even though the correlation factor was acceptable ($R^2 = 0.948$). This situation was expected since as the costs get lower, the rate at which the decrease continues should get lower as well. Hence, by analyzing other cost projection studies [15–17], it is decided that a 30% decrease in the rate of decrease of TIC is in order and is applied accordingly. The resulting equation was extrapolated until 2030 for the global average cost scenario. The high cost and low cost scenarios are determined to be ±20% of the average cost scenario which is in-line with the literature. Linear regression did not perform well on the data of Türkiye, with low correlation factor ($R^2 = 0.556$). However, the TICs of Türkiye was observed to be 10.5% percent higher compared to the world, on average. Hence the obtained projections for the world is multiplied by 1.1015 to obtain projections for Türkiye.

For solar PV, an exponential behavior was observed for both Türkiye's and global data. Hence, an exponential decay function was regressed in the form of Eq. (2) to the global data with the correlation factor $R^2 = 0.990$. In the regression, the dependent variable is the TIC and the independent variable the years. The obtained relation confirms literature on cost estimations [15,16]. Since there is only five TIC datapoints for Türkiye, and these points coincide with the global data, the same relation is utilized for projection of solar PV TICs of Türkiye, as well. The resulted model is taken as the average cost scenario. The

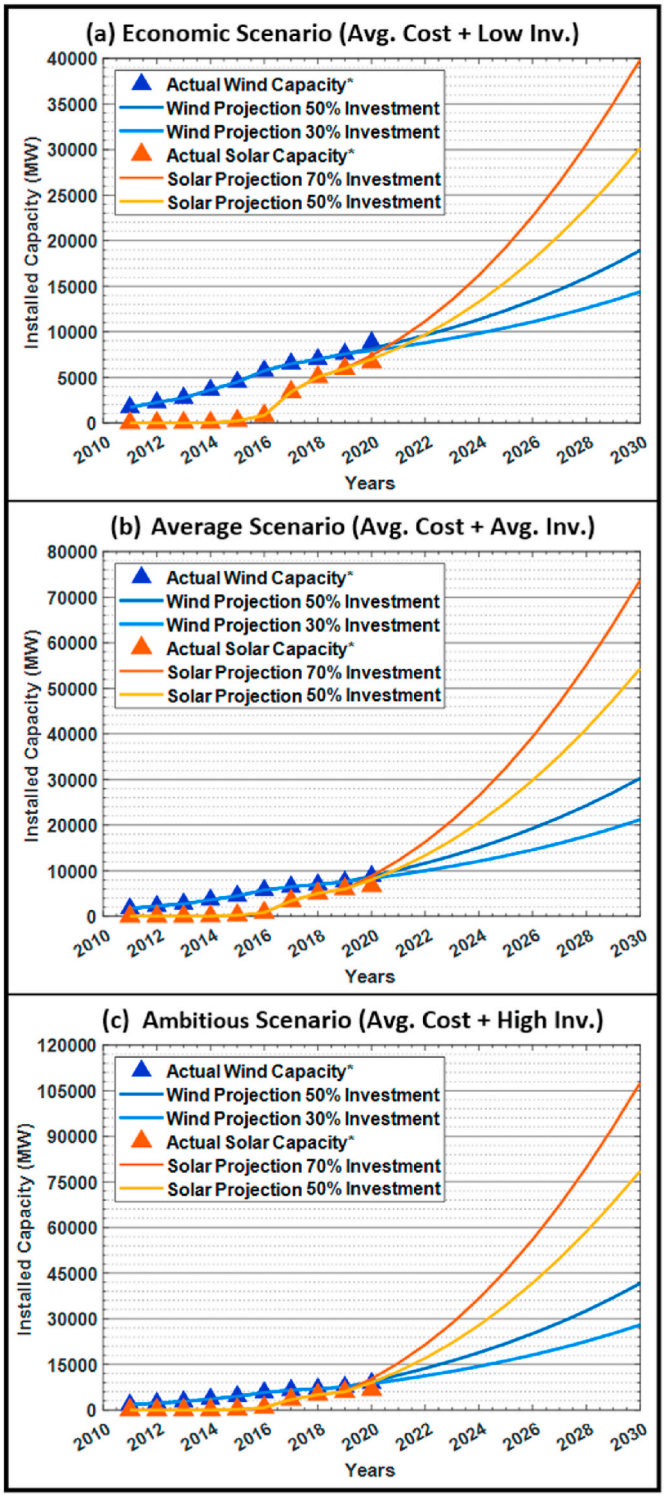


Fig. 5. Economic (a), average (b), and ambitious (c) projections for installed capacities of Türkiye's onshore wind and solar PV sectors.

average cost scenario is then multiplied by 1.3 and 0.7 for the construction of high and low cost scenarios, respectively.

$$y = y_0 + A\, e^{\frac{-(x-x_0)}{a}} \tag{2}$$

where y is the independent variable, x is the dependent variable, y_0, x_0, A, and a are constants that can be determined arbitrarily or by regression.

2.3. Capacity estimations

To estimate the annual installed capacity of Türkiye for each scenario, Eq. (1) can be rewritten as Eq. (3). Note that in calculation of the annual capacity changes, the total investment is utilized for onshore wind and solar PV, separately. Hence, the annual installed capacity changes only show what will happen if 100% of the money is invested on that energy sector and 0% on the other. Thus, it is important to determine to which percentage the investments will take place. As can be seen from the cost projections of this study, solar PV technologies are expected to continue being relatively inexpensive compared to the onshore wind. This cost advantage will likely result in a more solar PV focused economy. Consequently, in this study, the investment distribution possibilities of 50%/50% and 30%/70% onshore wind to solar PV ratio are investigated.

$$\Delta Cap(t) = Cap(t) - Cap(t-1) = \frac{Inv(t-1)}{TIC(t-1)} \tag{3}$$

With the obtained capacity changes, uncountably many scenarios may be generated by choosing different combinations of investment and cost scenarios for each year with different investment percentages for onshore wind and solar PV technologies. In this work, 5 of these scenarios is simulated and analyzed in detail for 2 different investment distributions, which are deemed the most helpful to the researchers and policymakers. These scenarios are described as follows:

- **Economic Scenario:** Türkiye will be investing according to the low investment scenario while the costs behave according to the average cost scenario for all years. This projection is suitable for determination of minimum targets.
- **Average Scenario:** Türkiye will be investing according to the average investment scenario while the costs behave according to the average cost scenario for all years. This is the most likely case for the following years.
- **Ambitious Scenario:** Türkiye will be investing according to the high investment scenario while the costs behave according to the average cost scenario for all years. This scenario shows how the possible improvements in the capacity with the added efforts from Türkiye.
- **Best-Case Scenario**: Türkiye will be investing according to the high investment scenario while the costs behave according to the low cost scenario for all years. This scenario yields the annual upper limits for installed capacities, which are unlikely to be reached.
- **Worst-Case Scenario:** Türkiye will be investing according to the low investment scenario while the costs behave according to the high cost scenario for all years. This scenario yields the annual lower limits for installed capacities, which are likely to be exceeded.

3. Results and discussion

3.1. Investment scenarios for Türkiye

The investment amounts for onshore wind and solar PV between the years 2011–2019 are evaluated as explained in section 2.1. The results are given in Table 2, in comparison with the IRENA's total renewable energy public finance flows. As can be seen from the table, our results agree with the IRENA's analysis. It is observed that in 2016, by the inclusion of over 2500 MW of solar PV (see Table 1) with the calculated investment of 4.1 billion $, solar energy has gained immense importance for energy sector of Türkiye. The table clearly shows that the investments in the solar PV sector has negatively affected the increasing investments in the onshore wind sector. While the investment trends in the onshore wind and solar PV sector show fluctuations, the trend of total investments seems unchanged except for 2016. Thus, the total investments are projected in this study for the investment scenarios.

The cost projections for the average, high, and low investment scenarios are given by Eqs. (4)–(6), respectively. These projections are

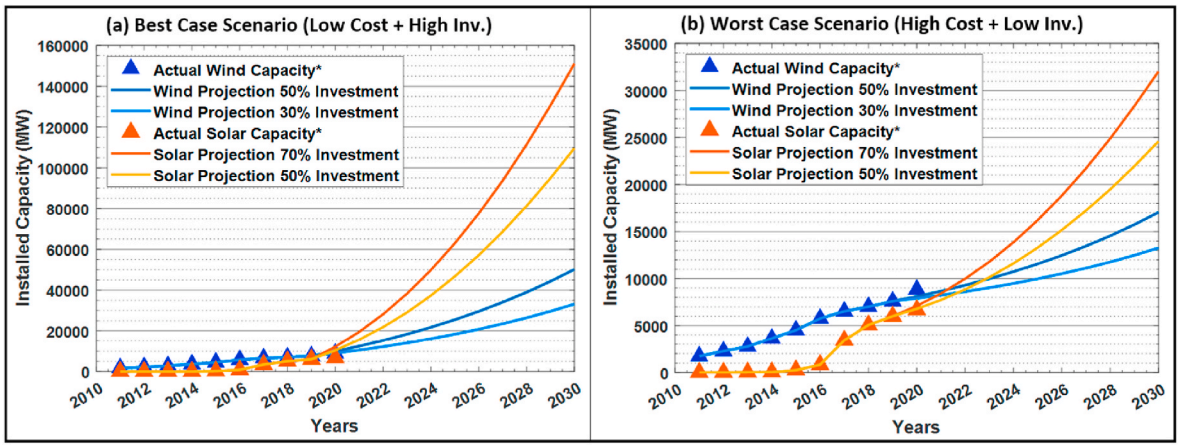


Fig. 6. Best case (a) and worst case (b) scenarios for installed capacities of Türkiye's onshore wind and solar PV sectors.

Table 4
Comparison of scenarios' installed capacities in 2030. * [29] **BAU: Business as Usual, ARES: Accelerated Renewable Energy Systems, CDP: Coal Phaseout [28] *** [27].

Scenarios	Installed Capacity (MW)	
	Onshore Wind	Solar PV
2020*	8832	6668
Economic 2030	14,400–18,930	30,180–39,850
Average 2030	21,200–30,270	54,350–73,700
Ambitious 2030	28,010–41,620	78,530–107,550
Best Case 2030	33,110–50,120	109,620–151,070
Worst Case 2030	13,260–17,040	24,600–32,030
BAU 2030**	16,979–29,224	19,796–34,334
ARES 2030**	29,224	34,334
CPD 2030**	29,224–32,224	34,334–41,334
Erat 2030***	25,000	38,000

illustrated in Fig. 1 with respect to the calculated total investments. The unchanged trend of the total investments and the exceptional year of 2016 can be seen more clearly in the figure. While the removal of 2016 data point for the regression is possible in a mathematical perspective, the above average investment at this year shows that Türkiye has the capacity to invest more in the renewable energy sector. Hence, the effect of this data is kept on the applied regression.

$$Inv_{avg}(t) = 10^5(0.0028\,t - 5.5651) \tag{4}$$

$$Inv_{high}(t) = 1.5\;Inv_{avg}(t) \tag{5}$$

$$Inv_{low}(t) = 0.5\;Inv_{avg}(t) \tag{6}$$

where $Inv_{high}(t)$, $Inv_{avg}(t)$, and $Inv_{low}(t)$ yields the investment amount for high, average, and low cost scenarios at the year t, respectively.

3.2. Total installed cost projections

3.2.1. Onshore wind

The global projection of TIC for average, high, and low cost scenarios for onshore wind are given by Eqs. (7)–(9), respectively. For Türkiye, the projections for low, average, and high cost scenarios are given by Eq. (10)–(12), again respectively. These projections are illustrated in Fig. 2. According to the projections, in 2030, the TIC for the world and Türkiye is expected to be below 1200 $/kW and 1300 $/kW, respectively. These estimations are well in line with the literature [15–17]. The TIC of the onshore wind may be as low as 750 $/kW in 2030, which would further increase its economic competitiveness.

$$Cos\;t_{wind,avg,world}(t) = \mathrm{f} \bullet \mathrm{P1} \bullet t + \mathrm{P0} + (1-\mathrm{f}) \bullet \mathrm{P1} \bullet \mathrm{t_0} \tag{7}$$

$$Cos\;t_{wind,high,world}(t) = 1.2\;Cos\;t_{avg}(t) \tag{8}$$

$$Cos\;t_{wind,low,world}(t) = 0.8\;Cos\;t_{avg}(t) \tag{9}$$

$$Cos\;t_{wind,low,Turkiye}(t) = 1.1015\;Cos\;t_{low,world}(t) \tag{10}$$

$$Cos\;t_{wind,avg,Turkiye}(t) = 1.1015\;Cos\;t_{avg,world}(t) \tag{11}$$

$$Cos\;t_{wind,high,Turkiye}(t) = 1.1015\;Cos\;t_{high,world}(t) \tag{12}$$

where t is time in years, f = 0.7 is the correction factor for 30% reduction in the TIC decrease rate, $t_0 = 2020$ is the initial year of the projection, and P1 = −64.64789 and P0 = 131992.95170 are the coefficients obtained by the linear regression.

3.2.2. Solar PV

The projection of TIC of solar PV globally and for Türkiye for the average, high, and low cost scenarios is given by Eqs. (13)–(15). The projections are illustrated in Fig. 3. As shown in the figure, the cost of solar PV has decreased drastically in the last decade. It is observed that as the costs get lower, the annual decrease of the costs has become smaller and smaller. According to the results, the costs are likely to stabilize around 500 $/kW in the next decade, possibly reaching as low values as 350 $/kW. Dissimilar to the onshore wind sector, the costs of solar PV in Türkiye followed identical trend with the world.

$$Cos\;t_{solar,avg}(t) = 417.5 + 3474\;e^{\frac{-(t-2011)}{4.678}} \tag{13}$$

$$Cos\;t_{solar,high}(t) = 1.3\;Cos\;t_{solar,avg}(t) \tag{14}$$

$$Cos\;t_{solar,low}(t) = 0.7\;Cos\;t_{solar,avg}(t) \tag{15}$$

3.3. Determination and assessment of 2030 targets for Türkiye

3.3.1. Evaluation of annual capacity changes

The annual installed capacity changes for each scenario are evaluated as explained in section 2.4. The results are illustrated in Fig. 4, where the blue stack, blue and yellow stacks combined, and all stacks combined represent the capacity changes with respect to low, average, and high cost scenarios, respectively. Here, it is observed that annual capacity changes increase over time, which is due to the combination of annually increasing investments and decreasing costs. The limits of installed capacity changes for each scenario is given in Table 3. In the table, it is seen that for the average scenario, the installed capacity changes will range between 740 and 3130 MW for onshore wind and 2040–9600 MW for solar PV. If the best case scenario is realized, annual installed capacity increase of 5860 MW and 20,590 MW seems possible

in 2030 for onshore wind and solar PV, respectively. The effects of these possibilities are discussed in detail in section 3.3.2, where the installed capacity projections are computed.

3.3.2. Determination and assessment of 2030 targets

By using the evaluated annual capacity changes, several scenarios are generated for determination of Türkiye's onshore wind and solar PV targets. In both the generated cost and investment scenarios, average cases will most likely take place. Hence, the economic, average, and ambitious scenarios are generated with the average cost scenario to assess the Türkiye's policy options, which are illustrated in Fig. 5. The best case and worst case scenarios are generated to determine the limits of this study in the case that the costs change drastically in the following years, which are presented in Fig. 6. According to the average scenario, the onshore wind and solar PV capacities can reach between 21,200 - 30,270 MW and 54,350–73,700 MW, respectively. These ranges are evaluated for each scenario, which are given in Table 4 where they are compared to the other recent projection studies for Türkiye [27,28]. It can be seen from the table that the onshore wind expectations of this study is well in line with the literature. However, the literature seems to underestimate the solar PV capacity according to the average scenario and agree with the economic scenario. This may stem from the fact that the installed solar PV capacity of Türkiye is currently less than installed onshore wind capacity, but the costs of the solar PV has dropped drastically in the last decade [32] and all the scenarios agree that the installed solar PV capacity will exceed the installed onshore wind capacity by 2030.

Since the average scenario has the most likely occurrence, determination of 2030 targets as 25,000 MW for onshore wind and 60,000 MW for solar PV seem achievable and the most suitable for Türkiye. If ambitious approach is desired, however, the targets of 35,000 MW and 90,000 MW for onshore wind and solar PV can be determined, however reaching these targets will likely prove to be challenging. In the post pandemic world with relatively high inflation and economic instabilities, economic scenario may be adopted as well. In this case, the targets may be determined as 17,000 MW for onshore wind and 35,000 MW for solar PV. However, energy security and increasing fuel prices could be more costly than adopting the average or ambitious scenarios for Türkiye in the mid to long term.

3.4. Overall discussion

In this study, the investment scenarios and cost projections for Türkiye is generated and these have been utilized extensively to determine the 2030 onshore wind and solar PV targets. The results are in line with the literature as Table 4 confirms, and the obtained models may successfully be utilized for Türkiye. This paper also provides a guideline for similar studies for other countries around the world. However, the reality is not idealized, and the TIC and LCOE of projects may vary noticeably with respect to location, climate, and landscape [33,34]. The network connection costs may also differ considerably and affect TIC [35]. Additionally, the feasibility of these projections should be considered as well. The economic and social criteria of the investments play significant role in the deployment of the renewable energy technologies [36,37]. Energy crisis and increasing electricity prices are the leading issues for the developing countries [38]. To address all these issues in the present work, several investment scenarios and cost projections are generated, and all the results are presented extensively. The correct utilization of the scenarios are left to the researchers and policymakers, who may analyze the mentioned variables of specific projects accordingly.

4. Conclusion and policy implications

This study highlights the importance of generation of reasonable and useful scenarios in accurately estimating the investments, costs, and capacity changes in onshore wind and solar PV for Türkiye. In the next decade, the capacity increases of the renewable energy of Türkiye will mainly be sustained from onshore wind and solar PV. If it is desired, Türkiye may increase its onshore wind and solar PV capacities up to 41,620 MW and 107,550, respectively, according to the ambitious scenario. However, achieving these values is likely to be challenging in terms of supplies and costs. The targets of 25,000 MW for solar PV and 60,000 MW of onshore wind are deemed to be the most appropriate for Türkiye and advised to be determined as such. Also, more conservative approaches are discussed in this study, however, the costs of not increasing the installed capacities may overweight the benefits due to the increasing fuel costs and energy security concerns. The main results of this study may be summarized as:

- Türkiye may increase its annual total investments to the renewable energy sector by 2030 up to 10 billion $ according to the high investment scenario. However, the most likely case according to the average scenario predicts the annual total investment as 6.5 billion $.
- The global TIC value for onshore wind is likely to reach 950$/kWh, while the global TIC value for solar PV is likely to stabilize around 500$/kWh.
- The costs of onshore wind for Türkiye is observed to be 10.15% higher than the world average in the last decade whereas the costs of solar PV is the same. This trend is expected to continue.
- According to the average scenario, the installed capacities of onshore wind and solar PV are expected to reach 25,000 MW and 60,000 MW in 2030, respectively.

Overall, this study aims to assist the researchers and policymakers by shedding light to the Türkiye's onshore wind and solar PV future for the sustainable development of the country's energy sector, and it can be used as a foundation for the analysis of onshore wind and solar PV technologies.

Credit author statement

Mert Akin Insel: Conceptualization, Data curation, Methodology, Formal Analysis, Investigation, Validation, Visualization, Writing – Original Draft, Writing – review & editing. **Hasan Sadikoglu:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision. **Mehmet Melikoglu:** Conceptualization, Methodology, Validation, Formal Analysis, Writing – review & editing, Supervision. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used in this study is referenced in the manuscript appropriately.

References

[1] S. bin Amin, Y. Chang, F. Khan, F. Taghizadeh-Hesary, Energy security and sustainable energy policy in Bangladesh: from the lens of 4As framework, Energy Pol. 161 (2022), https://doi.org/10.1016/j.enpol.2021.112719.

[2] S.I. Abba, B.G. Najashi, A. Rotimi, B. Musa, N. Yimen, S.J. Kawu, S.M. Lawan, M. Dagbasi, Emerging Harris Hawks Optimization based load demand forecasting and optimal sizing of stand-alone hybrid renewable energy systems– A case study of Kano and Abuja, Nigeria, Results Eng. 12 (2021), https://doi.org/10.1016/j.rineng.2021.100260.

[3] WHO, COVID-19 Slows Progress towards Universal Energy Access, 2021. Geneva, Switzerland, https://www.who.int/news/item/01-06-2022-report–covid-19-slows-progress-towards-universal-energy-access (accessed September 20, 2022).
[4] J. Abu Qadourah, Energy and economic potential for photovoltaic systems installed on the rooftop of apartment buildings in Jordan, Results Eng. 16 (2022), 100642, https://doi.org/10.1016/j.rineng.2022.100642.
[5] A.B. Setyowati, J. Quist, Contested transition? Exploring the politics and process of regional energy planning in Indonesia, Energy Pol. 165 (2022), https://doi.org/10.1016/j.enpol.2022.112980.
[6] A.N.M.F. Faisal, A. Rahman, M.T.M. Habib, A.H. Siddique, M. Hasan, M.M. Khan, Neural networks based multivariate time series forecasting of solar radiation using meteorological data of different cities of Bangladesh, Results Eng. 13 (2022), https://doi.org/10.1016/j.rineng.2022.100365.
[7] IEA, Net Zero by 2050 - A Roadmap for the Global Energy Sector, International Energy Agency, 2021. https://www.iea.org/reports/net-zero-by-2050 (accessed June 15, 2022).
[8] IEA, Global Energy Review 2021, International Energy Agency, 2021. https://www.iea.org/reports/global-energy-review-2021 (accessed June 15, 2022).
[9] A.M. Al-Falahat, J.A. Qadourah, S.S. Alrwashdeh, R. khater, Z. Qatlama, E. Alddibs, M. Noor, Energy performance and economics assessments of a photovoltaic-heat pump system, Results Eng. 13 (2022), https://doi.org/10.1016/j.rineng.2021.100324.
[10] A. Santa Catarina, Wind power generation in Brazil: an overview about investment and scale analysis in 758 projects using the Levelized Cost of Energy, Energy Pol. 164 (2022), https://doi.org/10.1016/j.enpol.2022.112830.
[11] K. Kabbabe Poleo, W.J. Crowther, M. Barnes, Estimating the impact of drone-based inspection on the Levelised Cost of electricity for offshore wind farms, Results Eng. 9 (2021), https://doi.org/10.1016/j.rineng.2021.100201.
[12] U.K. Elinwa, J.E. Ogbeba, O.P. Agboola, Cleaner energy in Nigeria residential housing, Results Eng. 9 (2021), https://doi.org/10.1016/j.rineng.2020.100103.
[13] J. Hernández-Moro, J.M. Martínez-Duart, Analytical model for solar PV and CSP electricity costs: present LCOE values and their future evolution, Renew. Sustain. Energy Rev. 20 (2013) 119–132, https://doi.org/10.1016/j.rser.2012.11.082.
[14] IRENA, Renewable power generation costs in 2019. https://www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019, 2020 (accessed June 29, 2022).
[15] L. Sens, U. Neuling, M. Kaltschmitt, Capital expenditure and levelized cost of electricity of photovoltaic plants and wind turbines – development by 2050, Renew. Energy 185 (2022) 525–537, https://doi.org/10.1016/j.renene.2021.12.042.
[16] R. Wang, S. Hasanefendic, E. von Hauff, B. Bossink, The cost of photovoltaics: Re-evaluating grid parity for PV systems in China, Renew. Energy 194 (2022) 469–481, https://doi.org/10.1016/j.renene.2022.05.101.
[17] IRENA, Future of wind. https://www.irena.org/publications/2019/Oct/Future-of-wind, 2019 (accessed June 29, 2022).
[18] R. Wiser, J. Rand, J. Seel, P. Beiter, E. Baker, E. Lantz, P. Gilman, Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050, Nat. Energy 6 (2021) 555–565, https://doi.org/10.1038/s41560-021-00810-z.
[19] H. Eroğlu, E. Cüce, Solar energy sector under the influence of Covid-19 pandemic: a critical review, J. Energy Syst. 5 (2021) 244–251, https://doi.org/10.30521/jes.942691.
[20] Fatpos Global, Impact of COVID-19 on onshore wind turbine: segmented : by application ; by end use ;, and region – global analysis of market size, share & trends for 2019–2020 and forecasts to 2031. https://www.reportlinker.com/p06272866/Impact-of-COVID-19-on-Onshore-Wind-Turbine-Segmented-By-application-by-end-use-And-Region-Global-Analysis-Of-Market-Size-Share-Trends-For-And-Forecasts-To-2031.html, 2022 (accessed June 30, 2022).
[21] R. Ling-zhi, Z. xin-gang, Y. Xin-xuan, Z. Yu-zhuo, Cost-benefit evolution for concentrated solar power in China, J. Clean. Prod. 190 (2018) 471–482, https://doi.org/10.1016/j.jclepro.2018.04.059.
[22] M. Melikoglu, B. Turkmen, Food waste to energy: forecasting Turkey's bioethanol generation potential from wasted crops and cereals till 2030, Sustain. Energy Technol. Assessm. 36 (2019), https://doi.org/10.1016/j.seta.2019.100553.
[23] C. Difiglio, B.Ş. Güray, E. Merdan, Turkey Energy Outlook 2020, TEO Book Printing, 2020.
[24] TEIAS, Turkey Electricity Production-Consumption 2020 Statistics, Turkiye Elektrik Iletim A.S., 2021. https://www.teias.gov.tr/turkiye-elektrik-uretim-iletim-istatistikleri (accessed June 15, 2022).
[25] M. Melikoglu, Vision 2023: Scrutinizing achievability of Turkey's electricity capacity targets and generating scenario based nationwide electricity demand forecasts, Energy Strategy Rev. 22 (2018) 188–195, https://doi.org/10.1016/j.esr.2018.09.004.
[26] M. Melikoglu, Hydropower in Turkey: analysis in the view of vision 2023, Renew. Sustain. Energy Rev. 25 (2013) 503–510, https://doi.org/10.1016/j.rser.2013.05.025.
[27] S. Erat, A. Telli, O.M. Ozkendir, B. Demir, Turkey's energy transition from fossil-based to renewable up to 2030: milestones, challenges and opportunities, Clean Technol. Environ. Policy 23 (2021) 401–412, https://doi.org/10.1007/s10098-020-01949-1.
[28] Shura, Integration of renewable energy into the Turkish electricity system, Shura (2022) 83–86. https://shura.org.tr/en/integration-of-renewable-energy-into-the-turkish-electricity-system/ (accessed June 21, 2022).
[29] IRENA, Renewable Energy Statistics 2021, 2021. https://irena.org/publications/2021/Aug/Renewable-energy-statistics-2021 (accessed June 22, 2022).
[30] C. Kul, L. Zhang, Y.A. Solangi, Assessing the renewable energy investment risk factors for sustainable development in Turkey, J. Clean. Prod. 276 (2020), https://doi.org/10.1016/j.jclepro.2020.124164.
[31] M. Xiao, T. Junne, J. Haas, M. Klein, Plummeting costs of renewables - are energy scenarios lagging? Energy Strategy Rev. 35 (2021) https://doi.org/10.1016/j.esr.2021.100636.
[32] IRENA, Renewable Power Generation Costs 2020, 2021. https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020 (accessed June 29, 2022).
[33] P. Lehmann, F. Reutter, P. Tafarte, Optimal Siting of Onshore Wind Turbines: Local Disamenities Matter, Helmholtz-Zentrum für Umweltforschung (UFZ), Leipzig, 2021. http://hdl.handle.net/10419/240195.
[34] J.M. Weinand, R. McKenna, H. Heinrichs, M. Roth, D. Stolten, W. Fichtner, Exploring the trilemma of cost-efficiency, landscape impact and regional equality in onshore wind expansion planning, Adv. Appl. Energy 7 (2022), https://doi.org/10.1016/j.adapen.2022.100102.
[35] R. McKenna, J.M. Weinand, I. Mulalic, S. Petrović, K. Mainzer, T. Preis, H.S. Moat, Scenicness assessment of onshore wind sites with geotagged photographs and impacts on approval and cost-efficiency, Nat. Energy 6 (2021) 663–672, https://doi.org/10.1038/s41560-021-00842-5.
[36] J.M. Weinand, E. Naber, R. McKenna, P. Lehmann, L. Kotzur, D. Stolten, Historic drivers of onshore wind power siting and inevitable future trade-offs, Environ. Res. Lett. 17 (2022), https://doi.org/10.1088/1748-9326/ac7603.
[37] J.M. Weinand, R. McKenna, M. Kleinebrahm, F. Scheller, W. Fichtner, The impact of public acceptance on cost efficiency and environmental sustainability in decentralized energy systems, Patterns 2 (2021), https://doi.org/10.1016/j.patter.2021.100301.
[38] M. Sohail, H.N. Afrouzi, J. Ahmed, K. Mehranzamir, M. Tabassum, M.B. Mobin Siddique, A comprehensive scientometric analysis on hybrid renewable energy systems in developing regions of the world, Results Eng. (2022), 100481, https://doi.org/10.1016/j.rineng.2022.100481.