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POST VISION 2023: SCENARIO DEVELOPMENT AND SYSTEMS DESIGN FOR TURKEY ENERGY SECTOR TILL 2033

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Mert Akın İNSEL

Signature

Dedicated to my family, to whom i am grateful for their exceptional support
and to my wife, to whom i am grateful for her extraordinary love.

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I would like to express deep gratitude to my advisors Prof. Dr. Hasan Sadıkoğlu and Prof. Dr. Mehmet Melikoğlu for their contributions, both to this study and to my life.

Mert Akın İNSEL

TABLE OF CONTENTS

LIST OF SYMBOLS vii

LIST OF ABBREVIATIONS viii

LIST OF FIGURES ix

LIST OF TABLES xi

ABSTRACT xii

ÖZET xiv

1 INTRODUCTION 1

1.1 Literature Review 1

1.1.1 Evaluation of Costs in Energy 2

1.1.2 Global Overview of Renewable Energy Technologies 3

1.1.3 Renewable Energy Sector of Turkey 5

1.2 Objective of the Thesis 5

1.3 Original Contribution 7

2 METHODOLOGY 8

2.1 Scenario Generation 8

2.1.1 LCOE Projection Scenarios 8

2.1.2 Turkey's Investment Scenarios 9

2.1.3 Modelling of LCOE Projections 10

3 RESULTS AND DISCUSSION 13

3.1 Global LCOE Projections 13

3.2 Relationship between TCI and LCOE 19

3.3 Scenario Development for Turkey Energy Sector 23

3.3.1 100% Onshore Wind Investment 24

3.3.2 100% Solar PV Investment 25

3.3.3 Optimum Investment Scenario 25

3.3.4 Turkey's Renewable Energy Shares by 2033 28

3.4 Conclusion 30

REFERENCES **31**

PUBLICATIONS FROM THE THESIS **38**

LIST OF SYMBOLS

f	Economic Factor

LIST OF ABBREVIATIONS

CSP	Concentrated Solar Power
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
Inv.	Investment
LCOE	Levelized Cost of Electricity
LFP	Lithium Ferrophosphate
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
Sc.	Scenario
TCI	Total Capital Investment

LIST OF FIGURES

Figure 1.1 LCOE data of renewable energy technologies between the years 2010-2018 [21] 3
Figure 1.2 Energy capacity of Turkey between 2010-2019 [47] 6
Figure 1.3 Electricity production of Turkey between 2010-2018 [47] 6
Figure 1.4 The ratio of Turkey's electricity production to the energy capacity . 7
Figure 2.1 High, medium and low investment scenarios for Turkey [47] 9
Figure 3.1 LCOE projections of solar PV for the low cost, average cost and high cost scenarios [21] 14
Figure 3.2 LCOE projections of CSP for the low cost, average cost and high cost scenarios [21] 14
Figure 3.3 LCOE Projections of onshore wind for the low cost, average cost and high cost scenarios [21] 16
Figure 3.4 LCOE Projections of offshore wind for the low cost, average cost and high cost scenarios [21] 17
Figure 3.5 LCOE Projections of hydropower for the low cost, average cost and high cost scenarios [21] 18
Figure 3.6 LCOE Projections of bioenergy for the low cost, average cost and high cost scenarios [21] 19
Figure 3.7 LCOE Projections of geothermal for the low cost, average cost and high cost scenarios [21] 20
Figure 3.8 Relationships between LCOE and TCI for renewable energy technologies [21] 21
Figure 3.9 TCI values of solar PV and onshore wind energy in Turkey compared to the world average 24
Figure 3.10 Yearly capacity changes of renewable energy sector in Turkey, in a scenario that all the future investments are channelled to the onshore wind energy 24
Figure 3.11 Turkey's renewable electricity capacity by the end of 2033 with respect to the investment scenarios, if all the investment is channelled to the onshore wind energy sector, compared with the current renewable electricity capacity in 2019 25

Figure 3.12 Yearly capacity changes of renewable energy sector in Turkey, in a scenario that all the future investments are channelled to solar PV 26
Figure 3.13 Turkey's renewable electricity capacity by the end of 2033 with respect to the investment scenarios, if all the investment is channelled to the solar PV sector, compared with the current renewable electricity capacity in 2019 26
Figure 3.14 Yearly capacity changes of renewable energy sector in Turkey for optimum investment scenario 27
Figure 3.15 Turkey's renewable electricity capacity by the end of 2033 with respect to the investment scenarios, for optimum investment scenario 27

LIST OF TABLES

Table 3.1 Economical factor estimations of renewable energy technologies by region 23
Table 3.2 Turkey's renewable energy shares in 2033 according to the simulated investment scenarios 29

ABSTRACT

Post Vision 2023: Scenario Development and Systems Design for Turkey Energy Sector till 2033

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Department of Chemical Engineering
Master of Science Thesis

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Turkey currently provides 61.2% of its electricity demand. But, Turkey's energy demand increases at a faster rate when compared to the world average. As a result, Turkey continue its investments in order to achieve its goals regarding the energy efficiency and security. Since the non-renewable energy sources become more and more expensive compared to the renewable alternatives, and not yet utilized in the country, renewable energy will be the predominant source of energy in Turkey. Thus, in this study, we mainly focused on developing strategies for Turkey's renewable energy sector. We have looked beyond 2023, and determined attainable 2033 renewable energy targets for the country, by considering different technology cost and investment ability scenarios. In this study, firstly, up-to-date levelized cost of electricity (LCOE) projections are conducted considering the low cost, average cost, and high cost scenarios. Then, mathematical relations which directly link LCOE with the total capital investment (TCI) are constructed, which are shown to be sufficient for macro-economic calculations. An economical factor is defined and explained in detail, which can be used to regionalize the average LCOE cost data, and to evaluate the economic efficiency of individual projects. Some regional economical factors evaluated in this work, while the obtainment of the factor is explained. Then, by utilizing all these results, Turkey's renewable energy capacity changes are simulated for low, medium, and high investment scenarios. The electricity capacity of 2019 is compared to the estimated 2033 capacities. Finally, the attainability of these capacities were discussed, and suggestions for 2033 renewable energy targets were produced to

be used by researchers and policymakers.

Keywords: Levelized cost of electricity, renewable energy, total capital investment, cost projection

ÖZET

2023 Ötesi Vizyon: Türkiye Enerji Sektörü için 2033'e Kadar Senaryo Geliştirme ve Sistem Tasarımı

Mert Akın İNSEL

Kimya Mühendisliği Anabilim Dalı
Yüksek Lisans Tezi

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Eş-Danışman: Prof. Dr. Mehmet MELİKOĞLU

Türkiye halihazırda kendi elektrik talebinin %61,2'sini karşılamaktadır. Ancak Türkiye'nin enerji talebi dünya ortalamasına göre daha hızlı artmaktadır. Sonuç olarak Türkiye enerji verimliliği ve güvenliği ile ilgili hedeflerine ulaşmak için yatırımlarına devam etmektedir. Yenilenemeyen enerji kaynakları, yenilenebilir alternatiflere göre giderek daha pahalı hale geldiğinden ve henüz ülkede kullanılmadığından, yenilenebilir enerji Türkiye'de hakim enerji kaynağı olacaktır. Bu nedenle, bu çalışmada ağırlıklı olarak Türkiye'nin yenilenebilir enerji sektörü için strateji geliştirmeye odaklanılmıştır. Bu çalışmada, 2023'ün ötesi incelenmiş, farklı teknoloji maliyeti ve yatırım yeteneği senaryolarını göz önünde bulundurarak ülke için ulaşılabilir 2033 yenilenebilir enerji hedefleri belirlenmiştir. Bu çalışmada ilk olarak, düşük, ortalama ve yüksek maliyet senaryoları dikkate alınarak güncel seviyelendirilmiş elektrik maliyeti (LCOE) projeksiyonları yapılmıştır. Daha sonra, LCOE'yi toplam sermaye yatırımı (TCI) ile doğrudan ilişkilendiren ve makro-ekonomik hesaplamalar için yeterli olduğu gösterilen matematiksel ilişkiler inşa edilmiştir. Ortalama LCOE maliyet verilerini bölgeselleştirmek ve münferit projelerin ekonomik verimliliğini değerlendirmek için kullanılabilen ekonomik bir faktör tanımlanmış ve ayrıntılı olarak açıklanmıştır. Bu çalışmada bazı bölgesel ekonomik faktörler hesaplanmış ve bu faktörün elde edilme yöntemi anlatılmıştır. Daha sonra tüm bu sonuçlardan yararlanılarak Türkiye'nin yenilenebilir enerji kapasite değişiklikleri düşük, orta ve yüksek yatırım senaryoları için simüle edilmiştir. 2019 elektrik kapasitesi, tahmini 2033 kapasiteyle karşılaştırılmıştır. Son olarak, bu kapasitelerin

ulaşılabilirliği tartışılmış ve araştırmacılar ve politika yapıcılar tarafından kullanılmak üzere 2033 yenilenebilir enerji hedefi için öneriler üretilmiştir.

Anahtar Kelimeler: Seviyelendirilmiş elektrik maliyeti, yenilenebilir enerji, toplam sermaye yatırımı, maliyet projeksiyonu

1
INTRODUCTION

1.1 Literature Review

Turkey is an upper-middle-income country with population of 83.6 million [1, 2]. Turkey's electricity demand increases at a faster rate than the world average (5% per year, compared to 3% per year between 2000-2019) [3]. While Turkey can provide 61.2% of the electricity demand [4], the investments continue in order to achieve its goals regarding the energy efficiency and security [5]. 43.53% of Turkey's energy is produced from renewable energy sources [4] and Turkey has ambitious goals to increase this percentage even higher in the future such as producing 30% of the country's energy demand from renewables by 2023 [6–8]. The capacity increase of Turkey will mainly be focused on renewable energy, especially solar and wind energies since they have already reached the grid parity (as discussed in the following chapters). Thus, it is crucial to comprehensively analyze the cost of these renewable systems while strategizing the Turkey's energy sector after 2023.

Renewable energy sources have significant environmental and economic benefits [9, 10]. Raising social awareness about climate change and increasing demand for sustainable production and consumption boost renewable energy projects around the globe [11–15]. One by one, renewable energy projects have been reaching grid (or socket) parity [16]. This means that the levelized cost of electricity (LCOE) from renewable energy projects are becoming similar or lower than that of the LCOEs of non-renewable projects [16]. In the energy sector, LCOE and total capital investment (TCI) are the main indicators of project value [17]. These two parameters can be used to assess the feasibility of different renewable energy projects when other parameters such as greenhouse gas emissions are almost similar [11, 18–21]. This means that estimation of LCOE and TCI are crucial for strategizing future investments in this sector. As a result, the aim of this study is to generate up to date LCOE estimations for different renewable energy technologies alongside with novel semi-empirical relations between LCOE and TCI that can be utilized also for forecasting TCI.

In the literature, there are different studies on estimating LCOE and TCI of different energy projects [22–26]. The International Renewable Energy Agency (IRENA) examined the costs and markets of electricity storage in 2017 and estimated a cost reduction of more than 50% in lithium ferrophosphate (LFP) battery storage systems until 2030 [21]. A cost reduction at this magnitude will significantly decrease the grid integration costs and LCOE of renewable energy sources [21]. A renewable energy grid integration study for Japan and reported that more than 33% of the total energy production can be sustained from renewables by 2030 [27]. A similar grid integration plan was conducted for Turkey and costs/benefits of some flexibility options on the LCOE of renewable energy systems were analysed [28]. These grid integration plans were conducted according, and as a suggestion, to the government plans that were based on LCOE and TCI estimations of other studies [28]. Generally, LCOE of projects provide a single value for comparing financial side of different energy technologies, but these values are highly affected by local conditions [29, 30]. Thus, alternative methods must be developed for analysing LCOE and TCI of different renewable energy projects. As a result, in this study, a novel economical factor is defined, and it is evaluated for different regions of the world. This is done in order to overcome the issue of local comparability.

1.1.1 Evaluation of Costs in Energy

In the energy sector, LCOE and total capital investment (TCI) are the main indicators of project value [17]. These two parameters can be used to assess the feasibility of different renewable energy projects when other parameters such as greenhouse gas emissions are similar [11, 18–21].

While numerous studies are conducted in evaluating LCOE of each renewable technology, the relations obtained include many variables such as TCI, operating and maintenance costs, land prices, insurance costs, discount rate, tracking factor, annual degradation, fuel expenditures [18, 31]. In macro-economic perspective, these relations are not generally useful since retrieving the necessary information may be challenging or even impossible. In addition, the equations that can be obtained from the literature are complicated, and does not clearly represent the importance of TCI in computation of LCOE for renewable technologies. In this study, timeline data between 2010 and 2018 are used to derive LCOE as a function of only TCI. This is possible since the renewable cost of energy technologies is capital-intensive [18]. It is believed that the relations obtained in this study can be satisfactorily used in macroscale analysis, as a world average scenario. These relations may also be used with the defined novel economical factor in order to conduct regional or individual project analysis.

1.1.2 Global Overview of Renewable Energy Technologies

In the last decade, the LCOE of concentrated solar power (CSP) systems decreased significantly due to reduction in the cost of energy storage systems (see Figure 1.1). Yet, the cost of CSP is still much higher than that of other renewable energy sources. The global CSP capacity increased 8 folds and reached to 5.5 GW in 2018 [32]. This is equal to 1% of global solar PV capacity. The LCOE data for CSP shows a clear decreasing trend, which is expected to continue in the upcoming years.

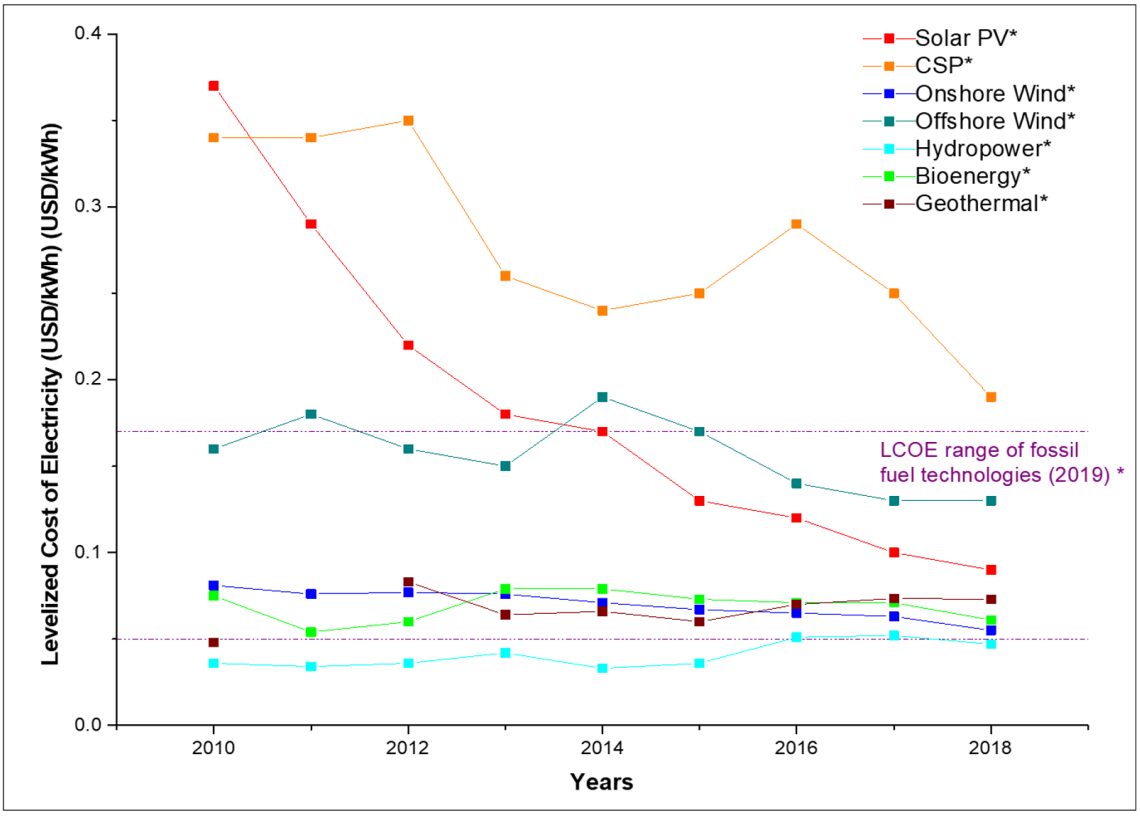


Figure 1.1 LCOE data of renewable energy technologies between the years 2010-2018 [21]

At the beginning of the last decade, onshore wind became economically competitive. Nowadays, onshore wind energy systems are used all around the world. The LCOE of onshore wind has been decreasing steadily (see Figure 1.1) mainly due to decreasing costs of energy storage systems [33]. This decline in LCOE boosted the number of projects and the global wind energy capacity increased from 198 GW to 591 GW between 2010 and 2018 [34].

The number of offshore wind projects is likely to increase in the next decade, which will add to the global cumulative know-how, and this will decrease the costs further down. There is a similarity between the relationships of onshore - offshore wind technologies and solar PV - CSP technologies [35]. The global capacity of offshore wind increased from 3.2 GW to 23.1 GW between 2010 and 2018 [32]. Yet, this is

only equal to 4% of the global wind installed capacity. The cost difference between the onshore and offshore wind results mainly from the construction difficulties of offshore wind power plants. Successful offshore wind energy projects completed in Europe pave the way for future projects [32]. The Dutch government aims to reach an offshore wind installed capacity of 4.5 GW by 2023 and 11.5 GW by 2030 [36]. This will also increase the current global capacity by about 35% [36]. LCOE data for offshore wind are also shown in Figure 1.1. It is expected that the LCOE of offshore wind projects will be between 0.033 and 0.15 USD/kWh in 2033, with a slowing rate to reach a minimum LCOE of 0.02 USD/kWh by 2050 [37].

Hydropower is a well-developed renewable energy technology [38]. In 2018, nearly 4200 TWh of electricity was generated from hydropower plants and the global capacity was nearly 1292 GW [39]. Hydropower plants have high capacity factor and electricity generation is relatively stable [8]. The LCOE of hydropower is already below the lower limit of LCOE for fossil fuel technologies (see Figure 1.1). In the last couple of years, a slight increase in the LCOE of hydropower was observed. This is related to changing trends in power generation. The number of the new hydropower projects is decreasing in developed countries, whereas it increases in developing countries. In 2018, more than half of the increase in global hydropower capacity was accounted from developing countries such as Pakistan, Brazil and Turkey [32]. It should be noted that slight oscillations in the LCOEs are quite normal for hydropower since the costs are site sensitive, and some projects may have relatively large LCOE values resulting from different causes such as faster project installation time and geography of the construction terrain [40]. It is expected that the LCOE of hydropower technologies will range between 0.031 and 0.072 USD/kWh in 2033 [37]. This data suggests that the LCOE may increase up to 0.08 USD/kWh if the current trend continues. However, there are large numbers of ageing facilities around the globe, which have been undergoing repairs, upgrades and modernization projects [41]. As a result, the global average LCOE of hydropower is likely to decrease in the following years with the inclusion of these data.

Energy generation from different types of biomass is well-established [42]. It has been reported that nearly 12.4% of the global energy consumption is sustained from biomass sources and about half of all renewable energy final consumption is provided from bioenergy sources [32]. Different levels of technology are required for bioenergy generation [1]. For the most advanced bioenergy projects, feedstock costs are the greatest contributor to the production costs, which range between 40% and 70% [43]. This share may increase even more with the developing bioenergy technologies [44]. Yet, with increasing number of projects and know-how development, the biomass procurement will likely to improve. Thus, an overall decrease in the LCOE of bioenergy

technologies is expected to continue in the upcoming years (see Figure 1.1).

Global electricity generation from geothermal sources was 89.3 TWh in 2018 and it was estimated that nearly the same amount of thermal energy was consumed in the same year [32]. In recent years, binary-cycle technologies are preferred partly due to the availability of using low temperature geothermal resources [45]. While usage of traditional resources have a LCOE range between 0.037 and 0.124 USD/kWh, this value may increase up to 0.453 USD/kWh with the inclusion of enhanced geothermal systems [46]. It is envisaged that enhanced geothermal systems with higher levels of environmental protection will cost significantly higher though and this may increase average LCOE values (see Figure 1.1).

1.1.3 Renewable Energy Sector of Turkey

In the last decade, Turkey has increased its renewable energy capacity and electricity production immensely by 157% and 76%, respectively. The increase mainly stems from hydropower, wind, and solar energy investments, as can be seen in Figure 1.2 and 1.3. The increase in the capacity higher than the increase in production, which is expected since the grid integration has its own challenges in itself [28]. With increasing grid integration, the production is likely to increase in the future even without any additional capacity increase. However, the electricity production is significantly lower in 2014, even though the increase in the capacity is steady. In order to investigate the reasons behind this outcome, the ratio of energy capacity to the electricity production is illustrated in Figure 1.4. Here, we can see that the capacity factor for all important renewable energies in Turkey (hydropower, solar, and wind) has decreased significantly, especially for solar energy where the decrease is about 68%. The capacity factor of the renewables have been increasing in the world, thus we may expect these ratios to increase in the future, resulting more electricity generation in Turkey.

1.2 Objective of the Thesis

Aim of this study is to provide up to date projection for the cost of renewable energy technologies around the world and provide means to obtain regional information from the worldwide data by comparison. Additionally, this study aims to provide an analysis of Turkey's renewable energy future, until 2033, which may be useful for the researchers and policy makers in the country.

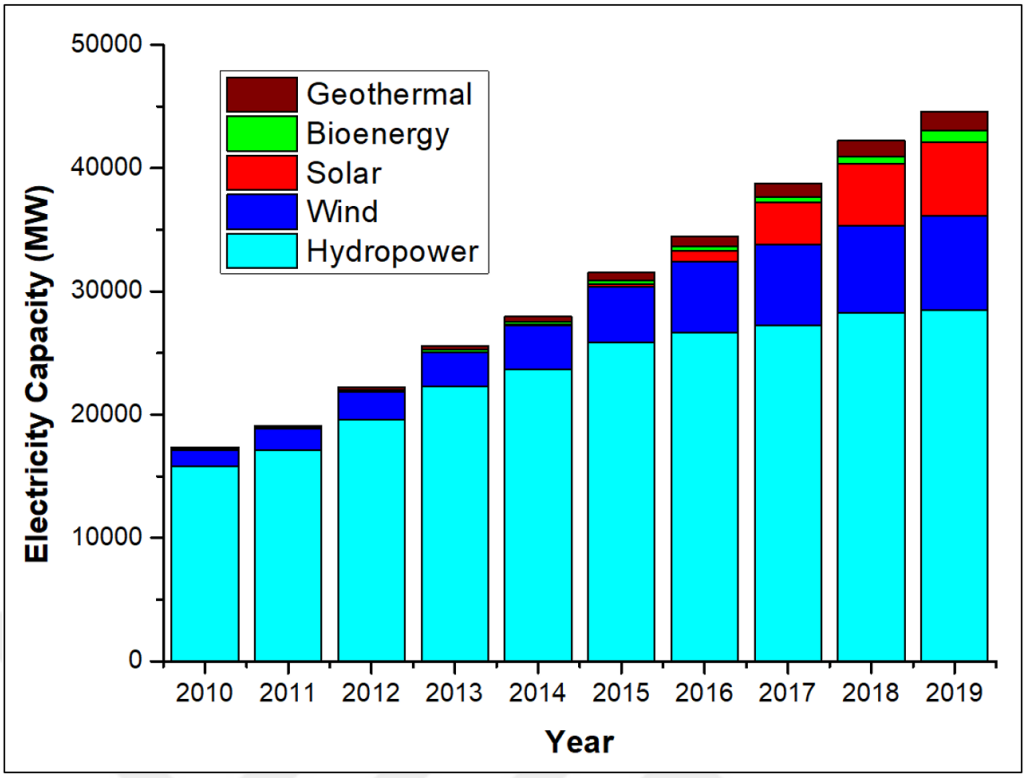


Figure 1.2 Energy capacity of Turkey between 2010-2019 [47]

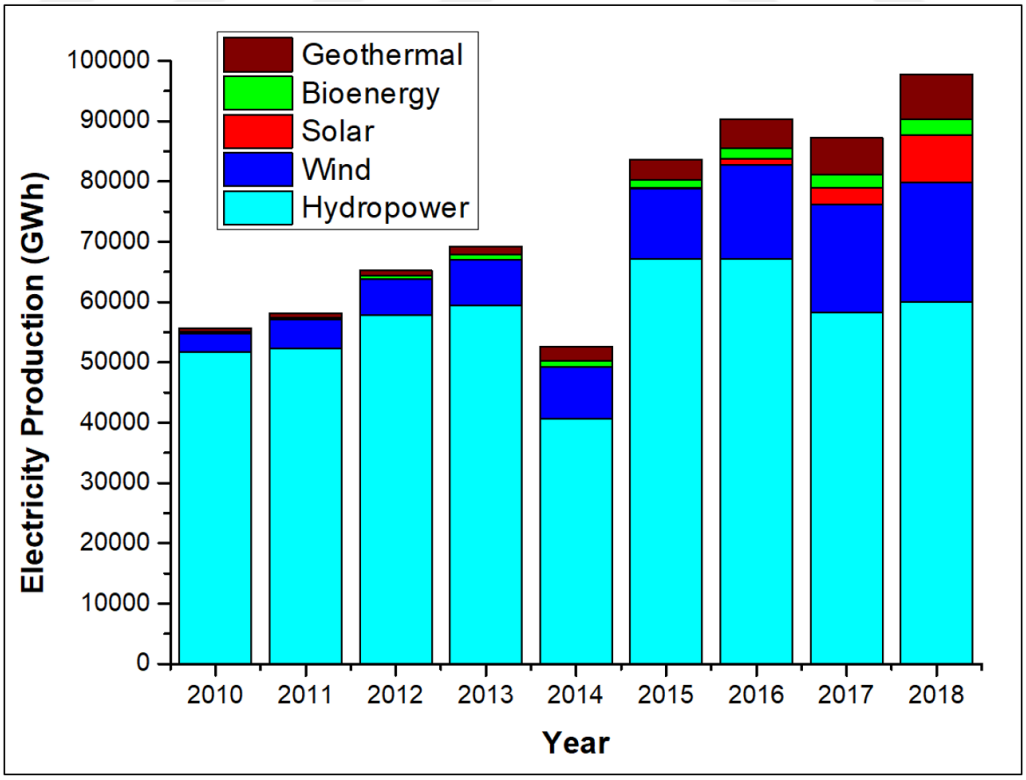


Figure 1.3 Electricity production of Turkey between 2010-2018 [47]

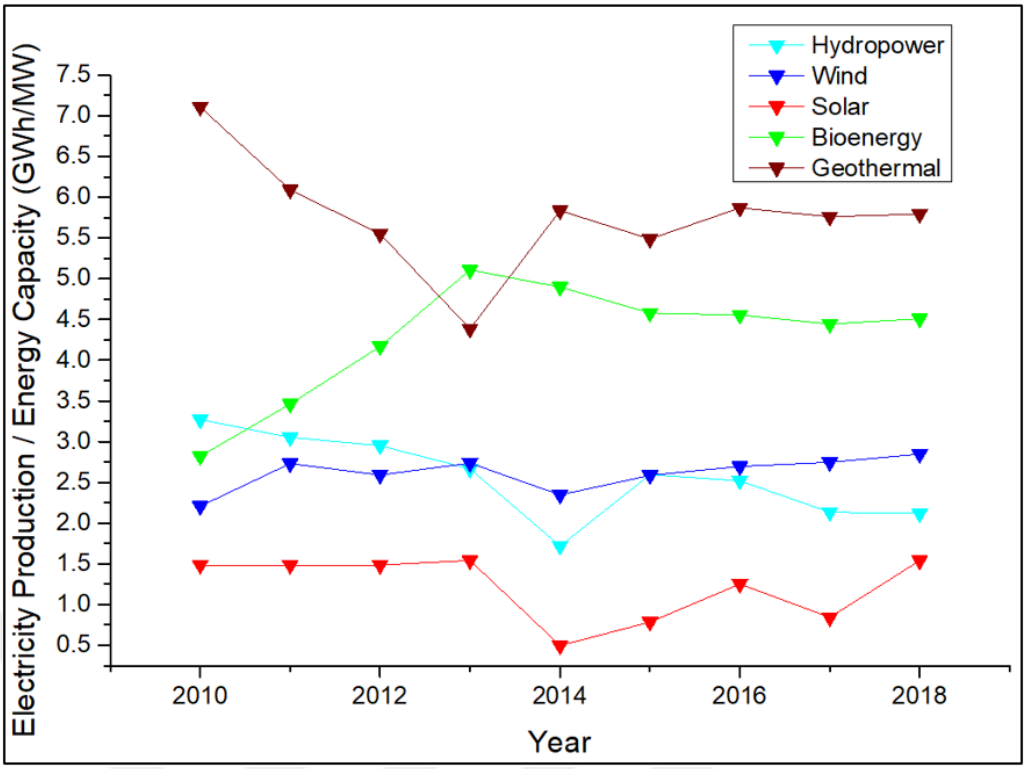


Figure 1.4 The ratio of Turkey's electricity production to the energy capacity

1.3 Original Contribution

In this study, LCOE of renewable energy technologies are forecasted till 2033 using timeline data between 2010 and 2018 with an aim to provide up to date information about this subject. Moreover, a novel economical factor is defined and evaluated for different regions in the world in order to provide local comparability of the current and estimated LCOE values. Finally, novel mathematical relations between TCI and LCOE for different renewable energy technologies are obtained from the same timeline data, where LCOE is simply expressed as a linear function of only TCI. As a final result, three investment scenarios generated for Turkey based on the previous years' investment amounts. These scenarios are simulated by utilizing the projected LCOE values and obtained functions. If Turkey choses to concentrate all of its focus on improving the onshore wind capacity, the share of wind energy may increase up to 35% in 2033. If, however, Turkey choses to focus on improving solar PV capacity, the share of solar energy may increase up to 31%. Attainable renewable share targets are also suggested for Turkey as 26% and 14% onshore wind and solar PV, respectively, by the year 2033.

2
METHODOLOGY

2.1 Scenario Generation

2.1.1 LCOE Projection Scenarios

The European Union plans to increase the share of renewables from 20% to 32% between 2020 and 2030 [48, 49]. The Japanese government plans to increase the share of renewables to 24% by 2030 [50]. Turkey aims to produce 30% of its electricity from renewables till 2023 [5]. Although these goals seem promising, it is important to achieve these goals while minimizing the costs in the long run. LCOE of the same project carried out in different locations can vary significantly [23]. This situation stems from the many differences such as climate, government policies, project site, etc. Thus, proposing a single scenario for LCOE projections is not generally useful. As a result, the following scenarios are generated in this study for analyzing different renewable energy systems:

1. Low cost scenario: This scenario is generated as the best-case scenario, and it is assumed that it will be realized with the planned technological improvements and country goals. This scenario should be used for technologically advanced countries with low levels of economic instability. In this case, technological developments have more direct impact on the project costs than any other factor. This scenario provides a lower limit for macroeconomic estimations.

2. Average cost scenario: This scenario should be used to estimate the world average LCOE. While there may be more projects in the developed countries with more ambitious goals, this is not likely to compensate the fact that the number of developing countries is higher than the developed countries. Hence, there will be more projects in the developing and least developed countries, which will push the average case to the higher cost scenario. Thus, rather than being in equidistance to low cost and high cost scenarios, this scenario is closer to the high cost scenario. This scenario can be assumed for developing countries with low-moderate economic instabilities. If the novel economical factor, which will be defined in section 3.2, is available, then it can

be utilized to estimate a regional LCOE by simply multiplying it with the LCOE values obtained using this scenario.

3. High cost scenario: In this scenario, the technological developments have little or no impact on project costs. This scenario can be used for least developed countries or developing countries with moderate-high levels of economic instability and high dependency on foreign countries for the required technological improvements. This scenario provides an upper limit for macroeconomic estimations.

2.1.2 Turkey's Investment Scenarios

When the data of Turkey's investment to the renewable energy sector between the years 2010 – 2019 is investigated, it is seen that lately, Turkey has been trying to prioritize the renewable energy sector. The amount of yearly investment has even reached 1400 million USD dollars in 2016, and is around 1000 million USD dollars in 2019. The economic effects caused by COVID-19 is not considered in this study since the outbreak's effects will depend gravely on the government responses and is yet unclear [51]. Thus, we investigate the following high, medium, low investment scenarios (see Figure 2.1).

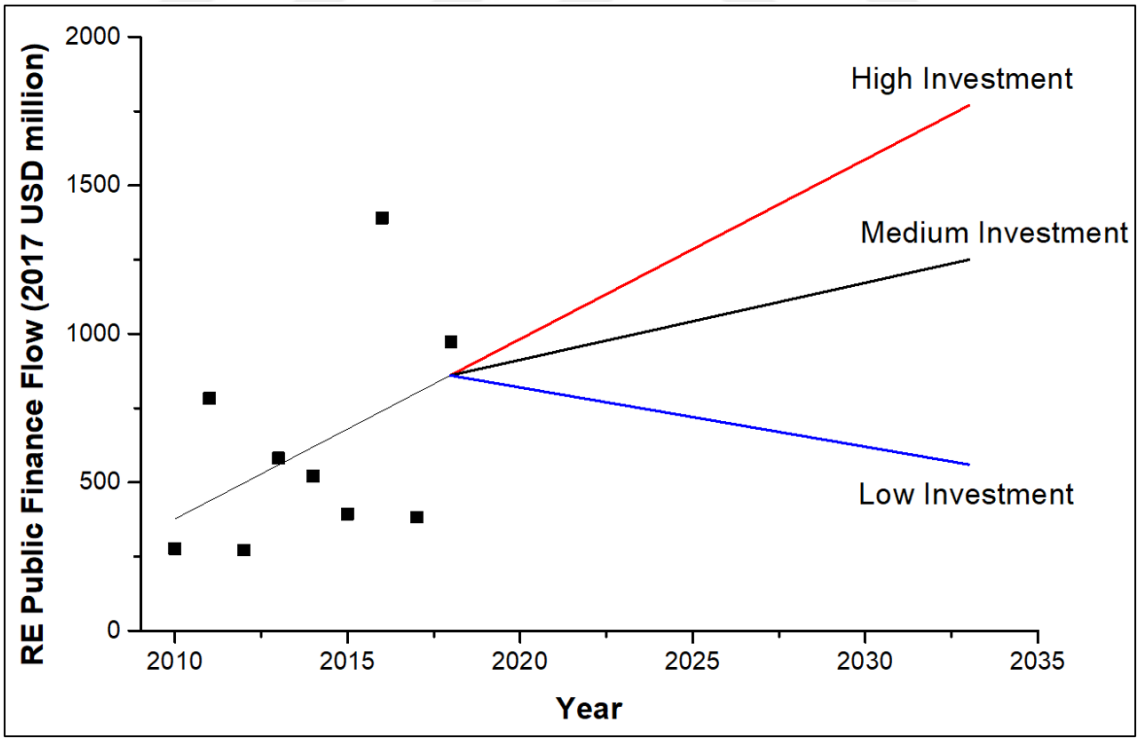


Figure 2.1 High, medium and low investment scenarios for Turkey [47]

2.1.3 Modelling of LCOE Projections

In order to obtain LCOE projections, different approaches were utilized for each renewable energy technology. For solar PV, first, an exponential decay function is regressed to the timeline data with R^2=0.99, which is shown in Equation 2.1. When this function is extrapolated, the LCOE value of 0.07 USD/kWh is reached at 2033. This value is in-line with other estimations of high cost scenarios of several studies [52–56]; consequently, it is selected as the high cost scenario of this study. For the low cost scenario, the rate of decrease of the LCOE in 2020 is assumed to be maintained in the following years, which is possible for developed countries [57]. In order to obtain this rate, the derivation of Equation 2.1 is evaluated at t=2020 as -0.004 USD/kWh per annum. The low cost scenario is generated with the line with whose slope is equal to this rate is extrapolated, where 0.03 USD/kWh is reached. Average cost scenario is generated in a similar manner, assuming the rate at year 2022 is maintained. All these extrapolations are represented in Figure 3.1.

$$LCOE = 0.07 + 0.29e^{\frac{-(t-2010)}{3.17}} \tag{2.1}$$

For CSP, variance of the timeline data is relatively high. Thus, the projections are started from 2016, to compensate for the vagueness of the data. Two linear regressions are conducted, one for the data between 2010-2018 and one for the data between 2013-2018. The extrapolation of the former regression selected as the average cost scenario and extrapolation of the latter regression is selected as the high cost scenario, until 2021. For the low cost scenario, the rate of decrease is evaluated for the data between 2015-2018 by a linear regression, and a line is simulated with its slope equal to this evaluated rate. After 2021, where the average cost reaches the upper limit of the fossil fuel range, the decrease rate is expected to slow down for all scenarios. The new rates are adjusted to obtain the low cost scenario estimation of 0.04 USD/kWh and high cost scenario estimation of 0.15 USD/kWh for LCOE in 2033, in which the proposed projections are coherent with the literature [18, 23, 58, 59]. All these projections are shown in Figure 3.2.

For onshore wind, the data shows a clear linear decrease between 2010-2018. Since the lower limit of fossil fuels have been reached, it is expected that maintaining this rate of decrease in the LCOE will be the best case in the next decade. However, when the last two years are investigated, there is a significant increase in the rate of decrease, which may infer rapid technological developments in the following three years. Thus, two separate linear regressions are applied to the whole timeline data and to the data of only years 2017 and 2018, and the resulting lines are extrapolated in order to

obtain high cost and low cost scenarios until 2021, respectively. At this point, high cost projections reach the lower limit of fossil fuel technologies, thus the rates are adjusted accordingly to coincide the low cost scenario projections with the best case explained above. The average case scenario is obtained by maintaining a ratio of 2:1 between its distances to the low cost and high cost scenarios since the world average tends to gravitate towards the upper limits of the estimations [21, 60, 61]. At the end, high cost scenario results a LCOE of 0.038 USD/kWh and low cost scenario results a LCOE of 0.014 in 2033, which is in accordance with the data from the literature [21, 62–64]. All these projections are shown in Figure 3.3.

For offshore wind, while the data has relatively high variance, there is a clear decrease in the LCOE in the last decade. The average rate of decrease between 2010-2018 is likely to be maintained for an average project, thus the average cost scenario coincides with the extrapolation of the line, which is regressed for the whole timeline data in 2033. However, when the data between 2014-2018 are investigated, the rate of decrease is significantly higher when compared to the overall rate of decrease. This indicates that the LCOE might decrease in this trend in the short term. The line regressed to this data is extrapolated for the low cost scenario, until 2022, where it intersects with the lower limit of LCOE of fossil fuel technologies. Thereon, the rate is adjusted to obtain a LCOE value of 0.03 USD/kWh, which is a realistic estimation of the cost in 2033 and in accordance with the literature [65, 66]. For the high cost scenario, the average rate of decrease between 2010-2018 is maintained until 2022, then the rate is adjusted similarly to the other scenarios. In the end, LCOE value of 0.10 USD/kWh is obtained for the high cost scenario in 2033. The difference between LCOE values of high cost and low cost scenarios in 2033 is relatively high when compared to the other renewable energy technologies, which stems from the high variance of the data and the ambiguity in estimating the construction costs in the future for the offshore projects. All these projections are shown in Figure 3.4.

Hydropower is a well-developed renewable energy technology with the LCOE values already bellow the lower limit of LCOE of fossil fuel technologies. The timeline data shows a clear but slight increase in the last decade and in the worst case this increase will continue with the construction-wise challenging projects. Hence, the extrapolation of the line, which is regressed to the whole data is used as the high cost scenario that results 0.08 USD/kWh in 2033 for the high cost scenario. For generating the low cost scenario, the data between 2016-2018 are selected. The rate of decrease in the LCOE between these years is calculated to be 0.002 USD/kWh per annum, which is an ambitious rate at these low cost values. Thus, extrapolation is conducted with approximately 40% slower rate than of the three-year data, which results 0.03 USD/kWh in 2033 for the low cost scenario. The average cost scenario

is then generated by maintaining 2:3 distance ratio to the high cost and low cost scenarios, respectively. The ratio is slightly higher than the one used in the onshore wind projections since the LCOE of hydropower technologies is not expected to change drastically in the next decade [37, 40, 41]. All these projections are shown in Figure 3.5.

Similar to the hydropower, bioenergy is also a well-developed technology. The LCOE values of this technology is close to the lower limit of LCOE of fossil fuel technologies and has been stable at this level in the last decade. However, there is a clear decrease when the data between 2013-2018 are investigated. It is possible that this decrease may continue in the following years. While there are several cost reducing improvements regarding to bioenergy technologies, no drastic change is expected of the costs in the following years [35, 37, 56, 67]. With this information in mind, the high cost scenario obtained by the extrapolation of the line regressed to the whole data resulted a LCOE value of 0.073 in 2033. Low cost scenario is generated by extrapolating the line regressed to the data between 2013-2018, until 2022, where this line intersects the lower limit of LCOE of fossil fuel technologies. After this point, the rate is decreased by 75%, resulting a LCOE value of 0.041 USD/kWh in 2033. The average cost scenario is obtained by using this decreased rate at the intersection of the low cost and high cost scenarios. All these projections are shown in Figure 3.6.

For geothermal, the timeline data shows a clear increase in the LCOE. The rate of increase is consistent and relatively high in the last decade, which stems from the increasing number of regulations in the countries to overcome the socioeconomic concerns [45, 46]. Thus, the worst-case scenario for the geothermal would be the continuation of this increase, which is represented as the high cost scenario. To this end, the line regressed to the whole data is extrapolated until 2033, resulting LCOE value of 0.10 USD/kWh in 2033. Low cost of geothermal in 2033 is estimated to be 40% less than this value and low cost scenario is obtained accordingly. The average cost is generated by maintaining 3:5 distance ratio to the high cost and low cost scenarios, respectively. All these projections are shown in Figure 3.7.

3
RESULTS AND DISCUSSION

3.1 Global LCOE Projections

In 2015, solar PV has attained grid parity and since then LCOE of solar PV had been continuing to decrease. The reduction in the costs in the last decade was more rapid than anyone at that time had expected [31]. The decay in the LCOE of solar PV is exponential, and with the decreasing differences throughout the years, it will stabilize at the lower end of the fossil fuel range. It is expected that the LCOE of solar PV will be between 0.02 and 0.08 USD/kWh in 2030 [68]. Hernández-Moro and colleagues stated that solar electricity costs will be reduced substantially till 2030 and settle down around the lower end of the fossil fuel range [18]. The analysis of timeline data and the studies found from the literature [52–54, 56], high cost, average cost and low cost scenarios proposed for solar PV are shown in Figure 3.1. As can be seen from this figure, the LCOE of solar PV will continue to decrease, but at a slower rate, reaching the value of 0.03 USD/kWh for the low cost scenario and 0.07 USD/kWh for the high cost scenario, in 2033.

CSP is an expensive technology when compared to other renewable technologies. However, the 44% decrease in the LCOE of CSP between 2010 and 2018 indicates that this will not be the case in the future. The IRENA expects a 36% decrease in the LCOE of CSP until 2025 [31]. The analysis of timeline data and the studies found from the literature [18, 23, 31, 59, 69], high cost, average cost and low cost scenarios for solar CSP are shown in Figure 3.2.

It is observed that variance of the timeline data is relatively high for LCOE of CSP. Thus, the projections are started from 2016, to compensate for the vagueness of the data. Two linear regressions are conducted, one for the data between 2010 and 2018 and one for the data between 2013 and 2018. The extrapolation of the former regression selected as the average cost scenario and extrapolation of the latter regression is selected as the high cost scenario, until 2021. For the low cost scenario, the rate of decrease is evaluated for the data between 2015 and 2018 by a linear regression,

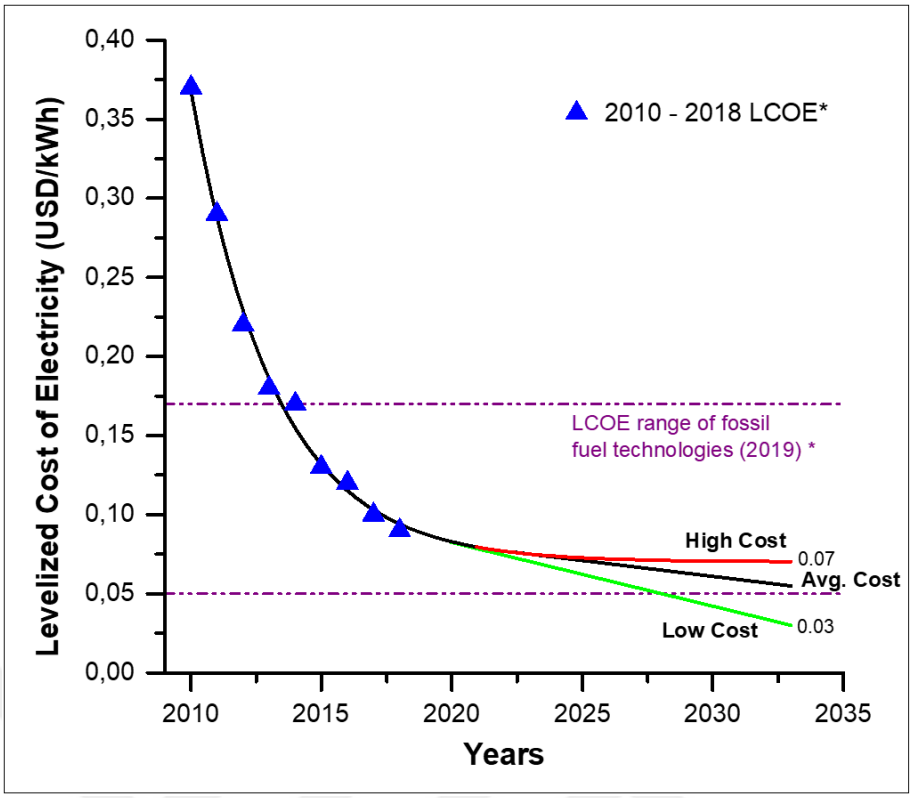


Figure 3.1 LCOE projections of solar PV for the low cost, average cost and high cost scenarios [21]

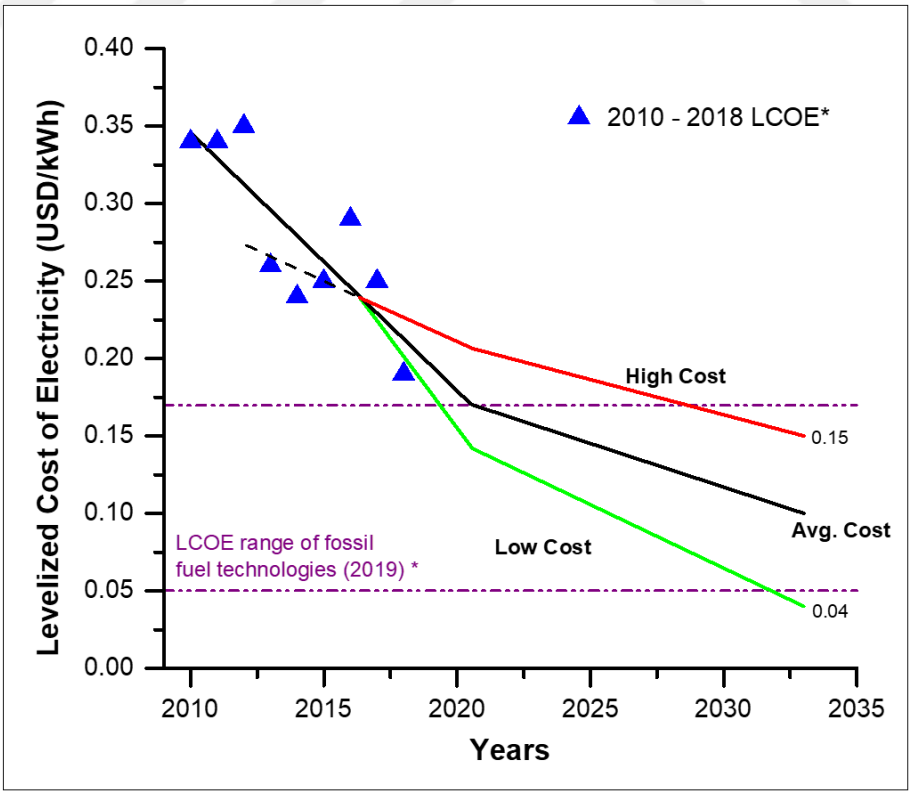


Figure 3.2 LCOE projections of CSP for the low cost, average cost and high cost scenarios [21]

and a line is simulated with its slope equal to this evaluated rate. After 2021, where the average cost reaches the upper limit of the fossil fuel range, the decrease rate is expected to slow down for all scenarios. The new rates are adjusted to obtain the low cost scenario estimation of 0.04 USD/kWh and high cost scenario estimation of 0.15 USD/kWh for LCOE in 2033, in which the proposed projections are coherent with the literature [18, 23, 31, 59, 69].

Consequently, it is expected that the LCOE for CSP will continue to decrease in the next decade but with a slower rate caused by the inherent logarithmic behavior of this kind of economic data. The National Renewable Energy Laboratory (NREL) reported that the expected values for LCOE of CSP in 2030 will be around 0.05 USD/kWh [58]. In the current study, it is estimated that the LCOE of CSP will reach 0.04 USD/kWh by 2033 based on the low cost scenario, which is very similar to the NREL estimate. However, the deviation of the LCOE data between 2010 and 2018 is relatively high; mainly, because of the low number of projects and low global capacity. Thus, in the current study, it is estimated that the LCOE will become 0.15 USD/kWh in 2033 for the high cost scenario. In both cases, it is expected that the grid parity will be reached by 2033, which will increase the number of CSP projects and will in turn decrease the costs even further closer to the cost of solar PV in the future.

The LCOE of onshore wind has been close to the lower limit of the LCOE of fossil fuel technologies and it has decreased nearly 22% between 2010 and 2018 with a linear behavior. This decrease is expected to continue with increasing capacity factors and decreasing TCI. From the analysis of the data and studies found from the literature [63, 64], high cost, average cost and low cost scenarios proposed in this study for onshore wind are shown in Figure 3.3.

For onshore wind, the data shows a clear linear decrease between 2010 and 2018. Since the lower limit of fossil fuels have been reached, it is expected that maintaining this rate of decrease in the LCOE will be the best case in the next decade. However, when the last two years are investigated, there is a significant increase in the rate of decrease, which may infer rapid technological developments in the following three years. Thus, two separate linear regressions are applied to the whole timeline data and to the data of only years 2017 and 2018, and the resulting lines are extrapolated in order to obtain high cost and low cost scenarios until 2021, respectively. At this point, high cost projections reach the lower limit of fossil fuel technologies, thus the rates are adjusted accordingly to coincide the low cost scenario projections with the best case explained above. The average case scenario is obtained by maintaining a ratio of 2:1 between its distances to the low cost and high cost scenarios since the world average tends to gravitate towards the upper limits of the estimations [21, 60,

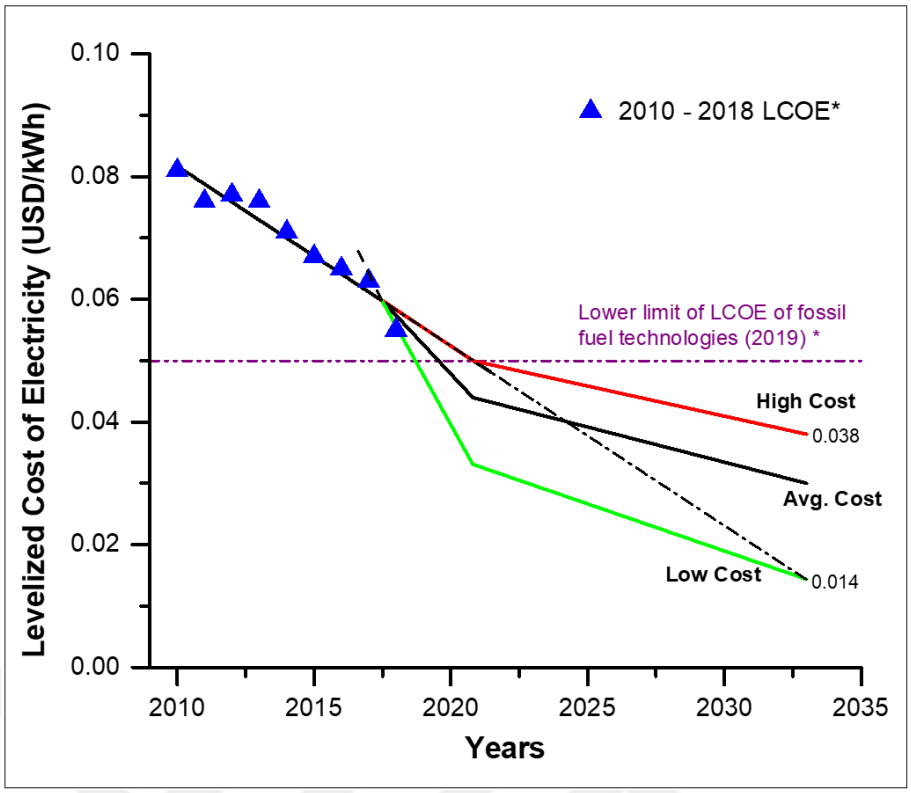


Figure 3.3 LCOE Projections of onshore wind for the low cost, average cost and high cost scenarios [21]

61]. At the end, high cost scenario results a LCOE of 0.038 USD/kWh and low cost scenario results a LCOE of 0.014 in 2033, which is in accordance with the data from the literature [21, 62–64]. The IEA expected that the LCOE of renewables to range between 0.02 and 0.04 USD/kWh in 2025 for projects in the United States [70], which is also in good agreement with the low cost estimation generated in this study. The IRENA also stated that the LCOE of onshore wind is expected to cost less than existing coal fired power plants [21].

Offshore wind is a technology has already reached grid parity. The LCOE data indicates a clear decrease in the LCOE from 2010 to 2018. The advancement in offshore (sea and/or ocean) construction technologies will be the most effective parameter regarding to the projects' approximation of the scenarios [31]. From the analysis of the data and studies found from the literature [31, 63, 65, 66], high cost, average cost and low cost scenarios proposed in this study for offshore wind are shown in Figure 3.4.

Hydropower is a well-established renewable technology, whose LCOE is already bellow the lower limit of LCOE of fossil fuel technologies. From the analysis of the data and studies found from the literature [30, 71], high cost, average cost and low cost scenarios proposed in this study for hydropower are shown in Figure 3.5. As can be

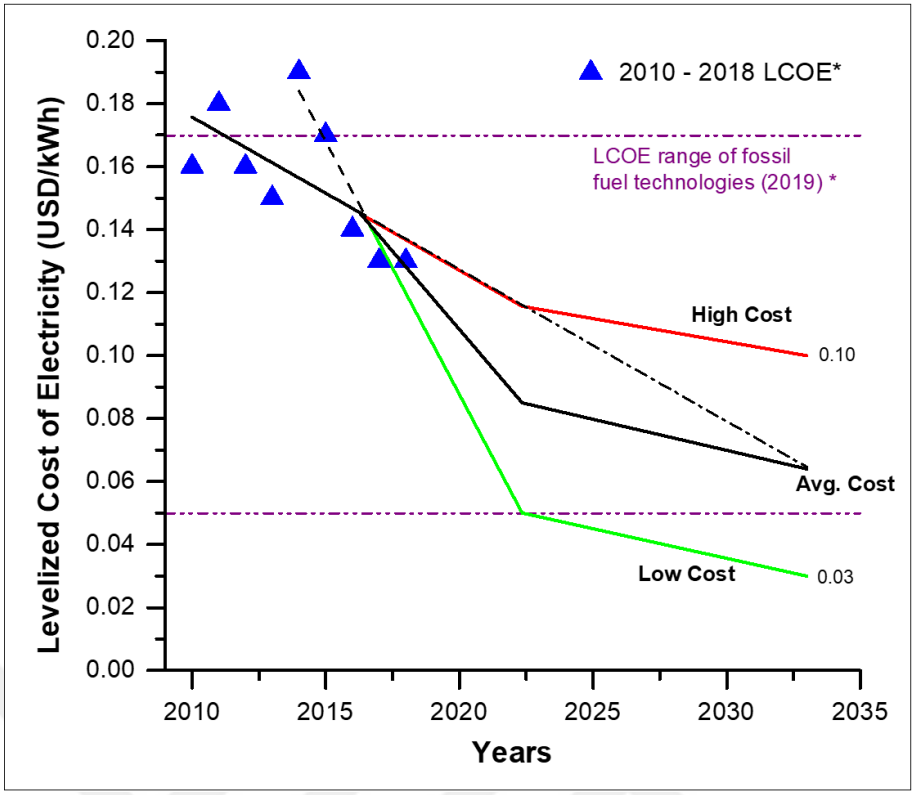


Figure 3.4 LCOE Projections of offshore wind for the low cost, average cost and high cost scenarios [21]

seen from this figure, it is expected that the average cost will slightly increase around the globe mainly due to the market shift in the industry from the developed countries to the developing countries.

The timeline data shows a clear but slight increase in the last decade and in the worst case this increase will continue with the construction-wise challenging projects. Hence, the extrapolation of the line, which is regressed to the whole data is used as the high cost scenario that results 0.08 USD/kWh in 2033 for the high cost scenario. For generating the low cost scenario, the data between 2016 and 2018 are selected. The rate of decrease in the LCOE between these years is calculated to be 0.002 USD/kWh per annum, which is an ambitious rate at these low cost values. Thus, extrapolation is conducted with approximately 40% slower rate than of the three-year data, which results 0.03 USD/kWh in 2033 for the low cost scenario. The average cost scenario is then generated by maintaining 2:3 distance ratio to the high cost and low cost scenarios, respectively. The ratio is slightly higher than the one used in the onshore wind projections since the LCOE of hydropower technologies is not expected to change drastically in the next decade [37, 40, 41].

Similarly to the hydropower, bioenergy is also a well-developed technology. The LCOE values of this technology is close to the lower limit of LCOE of fossil fuel technologies

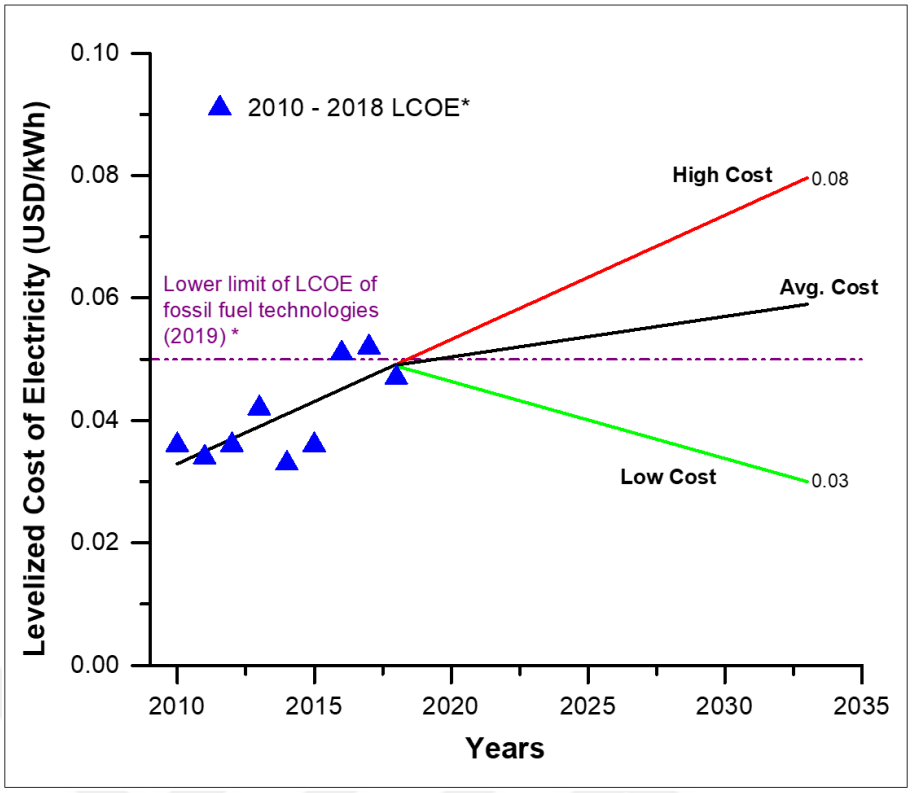


Figure 3.5 LCOE Projections of hydropower for the low cost, average cost and high cost scenarios [21]

and has been stable at this level in the last decade. NREL reports that LCOE of bioenergy technologies will be stagnant (starting from 2016) for the next 30 years, ranging between 0.07 and 0.11 USD/kWh [37]. However, a recent study suggested several potential improvements with modern bioenergy technologies, which will likely to decrease the LCOE in the upcoming years [72]. These improvements will be crucial for wider utilization of bioenergy due to potential reduction in the cost of other renewable energy sources.

LCOE estimation of bioenergy is challenging due to the fact that the main contributor to the cost is choice of the feedstock [67]. Yet, considering the fact that inexpensive feedstocks will be the choice of preference, it can be expected that the average LCOE of bioenergy technologies will decrease until 2033. From the analysis of the data and studies found from the literature [56, 67, 72], high cost, average cost and low cost scenarios proposed in this study for bioenergy are shown in Figure 3.6.

Geothermal is considered as a sustainable energy source but it also bears significant environmental risks such as water pollution, greenhouse gas emissions, particulate matter discharges, occupational hazards and etc. [73]. Managing these concerns adds additional costs, which in part increase the LCOE of geothermal projects. In a recent study by NREL it is projected that the LCOE of the traditional geothermal systems will

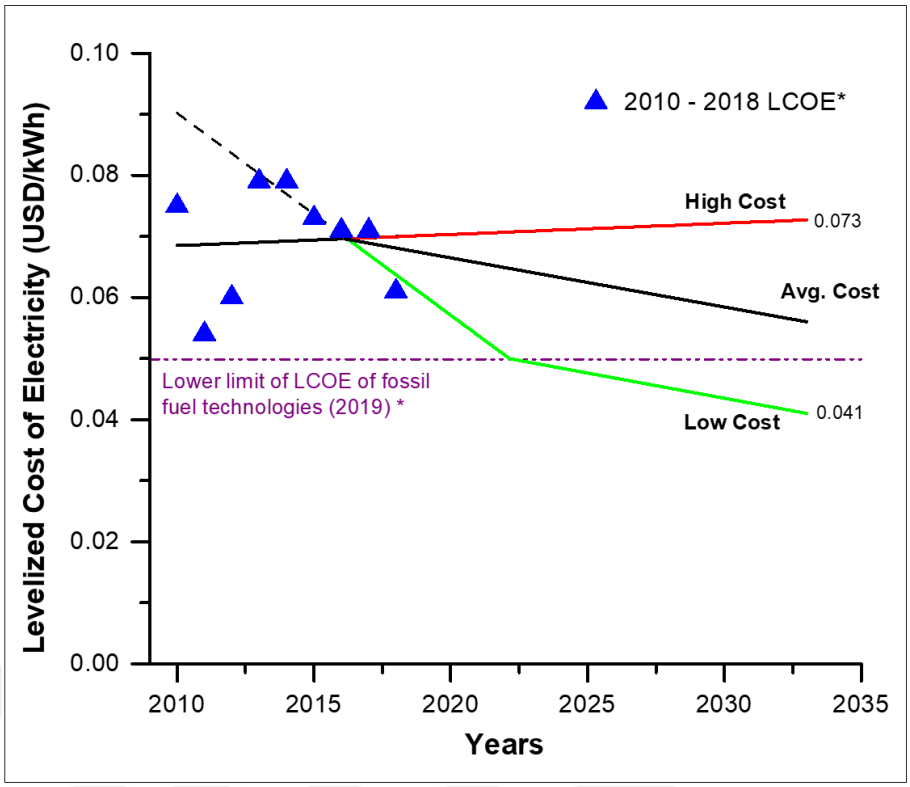


Figure 3.6 LCOE Projections of bioenergy for the low cost, average cost and high cost scenarios [21]

decrease in the following years, reaching a range between 0.03 and 0.1 USD/kWh [37]. From the analysis of the data and studies found from the literature [74, 75], high cost, average cost and low cost scenarios proposed in this study for geothermal energy are shown in Figure 3.7. While it is expected that the LCOE will increase to satisfy the regulations of countries to overcome the socioeconomic concerns, the technology is also likely to continue developing, thus slight decreases in the costs are also possible.

3.2 Relationship between TCI and LCOE

LCOE is a function of many parameters such as TCI, operating and maintenance costs, land prices, insurance costs, discount rate, tracking factor, annual degradation, fuel expenditures etc. [18, 31, 61]. These parameters affect the LCOE of individual projects and they are essential for accurate and precise estimations. However, in macroscale analysis, most of these parameters are redundant or unattainable. In addition, the equations obtained with these parameters are complicated and not convenient to be used in macroeconomic analysis. Thus, simpler LCOE formulations are required. Renewable energy sector is a capital-intensive sector, since operating costs are low when compared to the capital investments [18]. While investigating

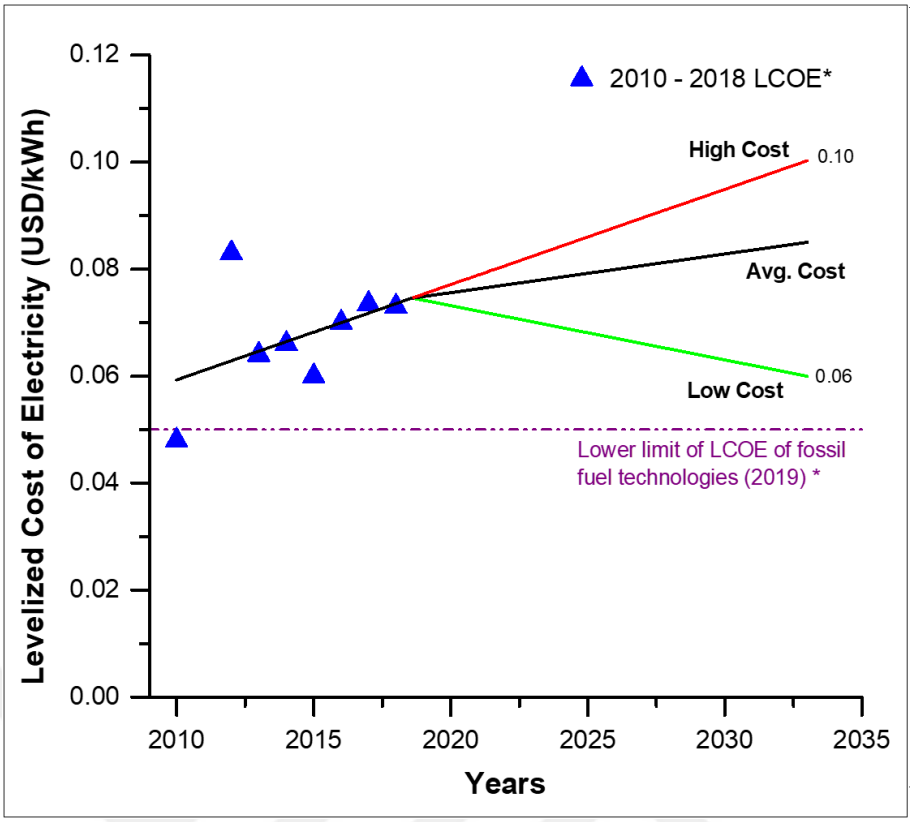


Figure 3.7 LCOE Projections of geothermal for the low cost, average cost and high cost scenarios [21]

the LCOE data, we have observed that the graphs of LCOE and TCI versus time show similar trends. Based on these premises, the relationships between LCOE and TCI are investigated in the current study based of the data obtained from IRENA. We show that the LCOE can be estimated from TCI quite sufficiently for macro-economic analysis by linear regression with acceptable R^2 values. These estimated relations (Equations 3.1-3.7) are reported bellow and illustrated in Figure 3.8.

Solar PV ($R^2 = 0.99$):

$$LCOE = 8.03471 \cdot 10^{-5} \cdot TCI - 0.01415 \tag{3.1}$$

CSP ($R^2 = 0.86$):

$$LCOE = 2.89135 \cdot 10^{-5} \cdot TCI + 0.06613 \tag{3.2}$$

Onshore wind ($R^2 = 0.95$):

$$LCOE = 4.96398 \cdot 10^{-5} \cdot TCI - 0.01590 \tag{3.3}$$

Offshore wind ($R^2 = 0.81$):

$$LCOE = 3.71925 \cdot 10^{-5} \cdot TCI - 0.02168 \tag{3.4}$$

Hydropower ($R^2 = 0.91$):

$$LCOE = 3.32758 \cdot 10^{-5} \cdot TCI - 0.00739 \tag{3.5}$$

Bioenergy ($R^2 = 0.92$):

$$LCOE = 1.33015 \cdot 10^{-5} \cdot TCI + 0.03844 \tag{3.6}$$

Geothermal ($R^2 = 0.93$):

$$LCOE = 1.33840 \cdot 10^{-5} \cdot TCI + 0.01749 \tag{3.7}$$

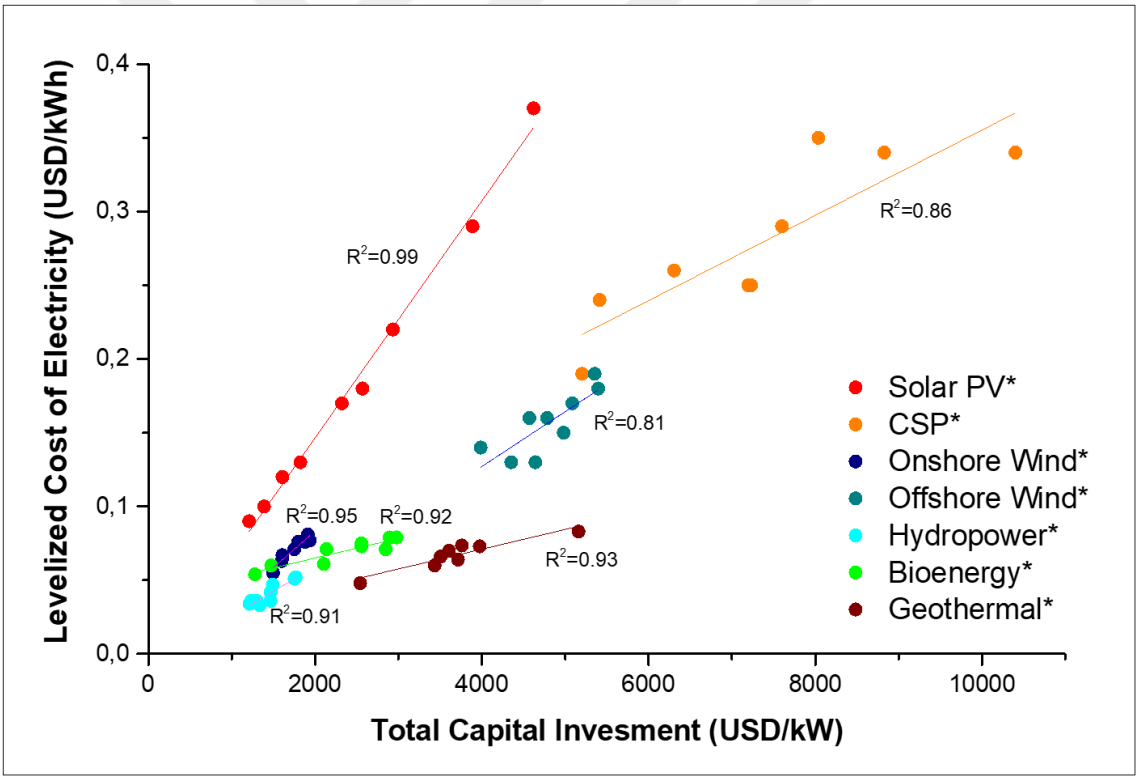


Figure 3.8 Relationships between LCOE and TCI for renewable energy technologies [21]

As can be seen from Figure 3.8, the linear regressions result a world average value for LCOE over the period of 2010 and 2018 regarding the projects with specific TCI. For example, if an average solar PV project has a TCI of 3500 USD/kW, then the LCOE of the project can be calculated from Equation 3.1 as 0.267 USD/kWh. Any project with the same TCI but higher LCOE can be assessed as yielding a higher cost than

the average case. To be more specific, let $LCOE_{actual}$ and TCI_{actual} denote the actual estimated values of LCOE and TCI for a project and $LCOE_{average}$ denote the world average LCOE value which is computed from the Equations 3.1-3.7, by using TCI_{actual}. Also, let the economic factor (denoted by f) be defined as the ratio of $\frac{LCOE_{actual}}{LCOE_{average}}$. Then, there will be three cases as follows:

- $f < 1$ implies that the project yields better LCOE than the world average for the same capital investment. In macro-economic analysis, this can be assumed for technologically advanced, developed countries with low levels of economic instability or countries with inexpensive labor. For example, in developed Asian countries, this value can be assumed 0.8 for onshore wind projects, since weighted average LCOE of this region is lower than the world average [21] in that proportion for the years 2016 and 2017.
- $f = 1$ implies that the project yields equivalent LCOE when compared to the world average for the same capital investment. In macro-economic analysis, this can be assumed for developed and developing countries with low-moderate economic instability levels.
- $f > 1$ implies that the project yields worse LCOE than the world average for the same capital investment. In macro-economic analysis, this can be assumed for developing countries with moderate-high levels of economic instability or countries with relatively expensive labor. In specific projects, this situation can stem from the selection of the difficult construction site or the faster project installation time.

It should be noted that economical factor f depends on many variables such as the renewable energy technology, country of the project, site availability for construction etc. Thus, the value of the factor may increase with challenging projects. The acceptance interval of this factor should be determined accordingly.

For macro-economic analysis, the value of the economical factor can be evaluated by simply obtaining the ratio of average LCOE of projects in that region to the world average for the specific technology. Table 3.1 represents some estimations of this factor for different regions and technologies. The obtained economic factor may as well be used with our LCOE projections to estimate region specific LCOE values until 2033.

Table 3.1 Economical factor estimations of renewable energy technologies by region

Region	$f_{SolarPV}$	f_{CSP}	$f_{Onshore}$	$f_{Offshore}$	f_{Hydro}	f_{Bio}	f_{Geo}
World Average	1	1	1	1	1	1	1
Africa	N/A	N/A	0.91	N/A	0.85	0.95	0.94
Brazil	N/A	1.06	0.97	N/A	0.63	0.95	N/A
Central America and Caribbean	N/A	N/A	0.94	N/A	1.29	0.95	0.87
China	0.67	0.95	0.76	0.9	0.54	0.82	N/A
Eurasia	N/A	1.162	1.12	N/A	0.76	0.95	N/A
Europe	0.93*	1.215*	1.17	0.94	1.74	1.12	N/A
India	0.63	0.79	0.99	N/A	0.72	0.80	N/A
Middle East	N/A	0.58*	N/A	N/A	1.03	0.95	N/A
North America	0.82*	1.109*	0.78	N/A	1.17	1.31	1.42
Oceania	N/A	1.37	0.89	N/A	1.84	0.95	N/A
Other Asia	1.56*	N/A	1.67	1.60*	0.69	0.95	0.82
Other South America	N/A	0.634	0.79	N/A	0.75	0.95	N/A

* For Europe, the average LCOE in France, Germany and Italy was used. For North America, LCOE in US is used. For Other Asia, the LCOE of Japan is used. For Middle East, LCOE in Saudi Arabia is used. For Oceania, LCOE in Australia is used.

** All the LCOE data for renewable energy technologies used in calculation of these estimations are obtained from IRENA [21, 60, 61].

3.3 Scenario Development for Turkey Energy Sector

The TCI of solar PV and wind energy is computed by using the average LCOE projections illustrated in Figure 3.1 and 3.3, and Equations 3.1 and 3.3. Then, the economic factors are determined for Turkey by using Table 3.1 as 1.12 and 1.162 for wind and solar PV, respectively. These TCI values are illustrated in Figure 3.9.

As can be seen in the Figure 14, the TCI of solar PV will be slightly lower than the TCI of wind energy until 2024, and from there on the wind energy will be comparably cheaper between 2024 and 2033. Notice that, that is not the case for the world. This figure also illustrates the significance of economic factor with regards to strategizing investments.

In the following sections, we will assume all of the investments are channelled to specific sector (solar PV or onshore wind) for a duration of time. Please note that this is not possible in application, and the purpose of these sections is to provide attainable targets for Turkey by the end of 2033.

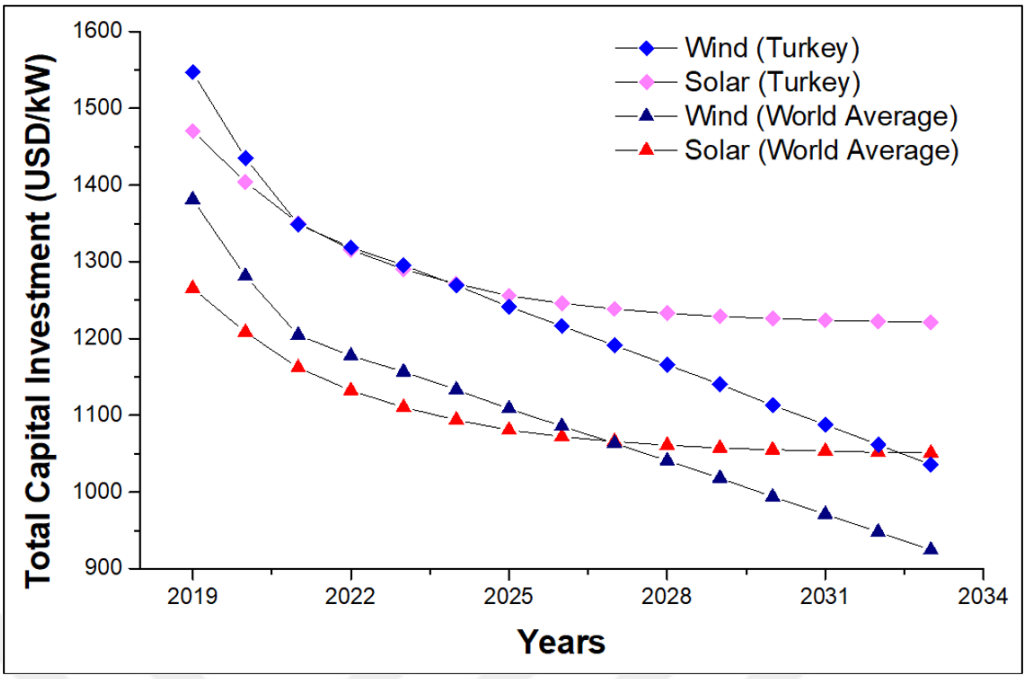


Figure 3.9 TCI values of solar PV and onshore wind energy in Turkey compared to the world average

3.3.1 100% Onshore Wind Investment

By using the TCI values given in Figure 3.9 and investment scenarios illustrated in Figure 2.1, assuming all the investments are channelled to the onshore wind energy sector, the yearly capacity increases of the Turkey's renewable energy sector for each scenario is represented in Figure 3.10.

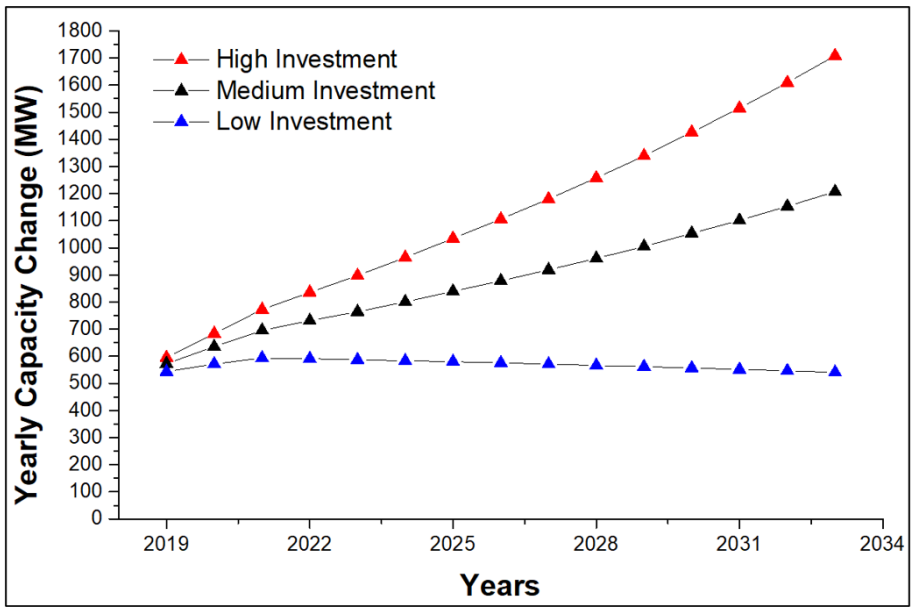


Figure 3.10 Yearly capacity changes of renewable energy sector in Turkey, in a scenario that all the future investments are channelled to the onshore wind energy

Thus, by the year 2033, the wind energy may increase by 112%, 175%, or 223% with

respect to the low, medium, and high investment scenarios, respectively. The resulting renewable electricity capacity of Turkey in 2033 is illustrated in Figure 3.11.

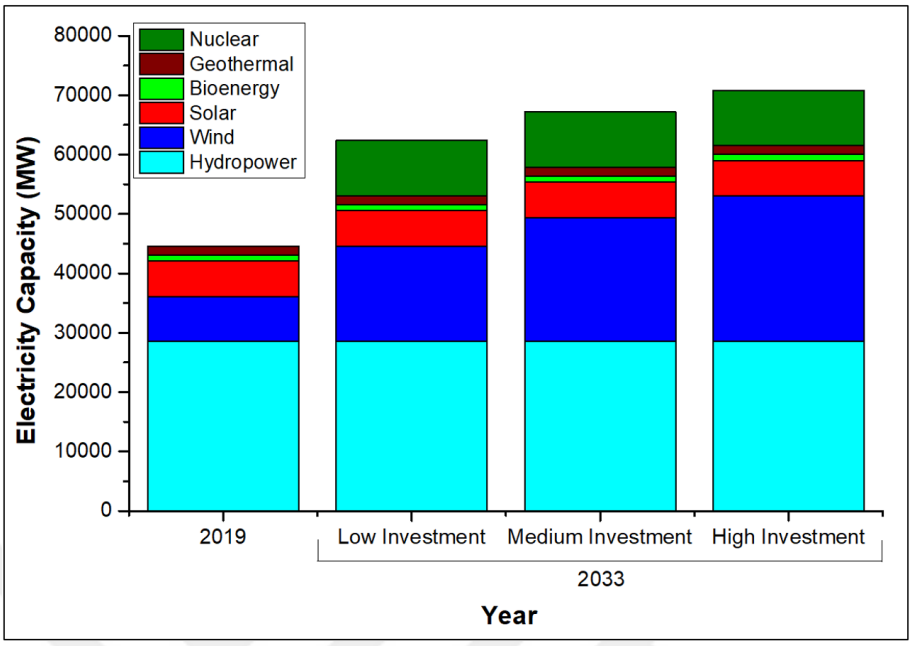


Figure 3.11 Turkey's renewable electricity capacity by the end of 2033 with respect to the investment scenarios, if all the investment is channelled to the onshore wind energy sector, compared with the current renewable electricity capacity in 2019

3.3.2 100% Solar PV Investment

By using the TCI values given in Figure 14 and investment scenarios illustrated in Figure 5, assuming all the investments are channelled to the onshore solar PV energy sector, the yearly capacity increases of the Turkey's renewable energy sector for each scenario is represented in Figure 3.12.

Thus, by the year 2033, the solar energy may increase by 136%, 210%, or 266% with respect to the low, medium, and high investment scenarios, respectively. As a result, the share of solar PV may be The resulting renewable electricity capacity of Turkey in 2033 is illustrated in Figure 3.13.

3.3.3 Optimum Investment Scenario

According to our projections, after 2024, the LCOE of wind energy will be significantly lower than that of solar PV for Turkey. Thus, if all the investments are channeled to solar PV in the first five years, then to the wind energy, the optimum investment scenario will be realized. In such case, the yearly capacity change of Turkey is represented in the following Figure 3.14.

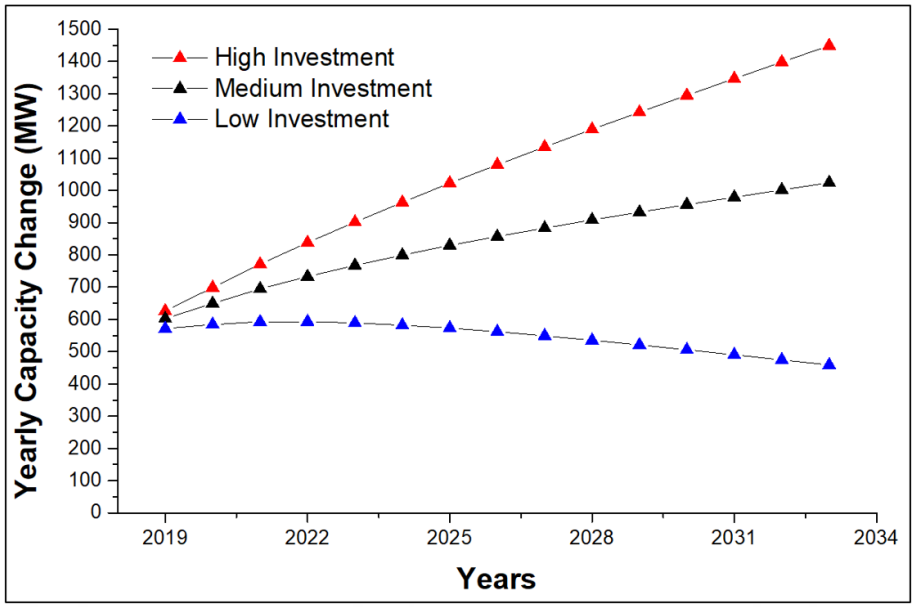


Figure 3.12 Yearly capacity changes of renewable energy sector in Turkey, in a scenario that all the future investments are channelled to solar PV

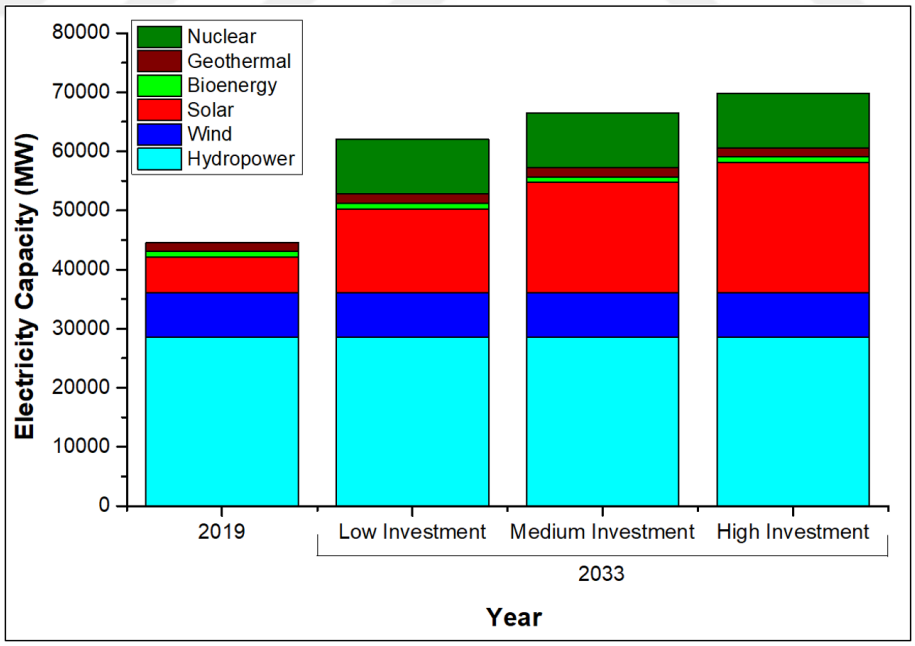


Figure 3.13 Turkey's renewable electricity capacity by the end of 2033 with respect to the investment scenarios, if all the investment is channelled to the solar PV sector, compared with the current renewable electricity capacity in 2019

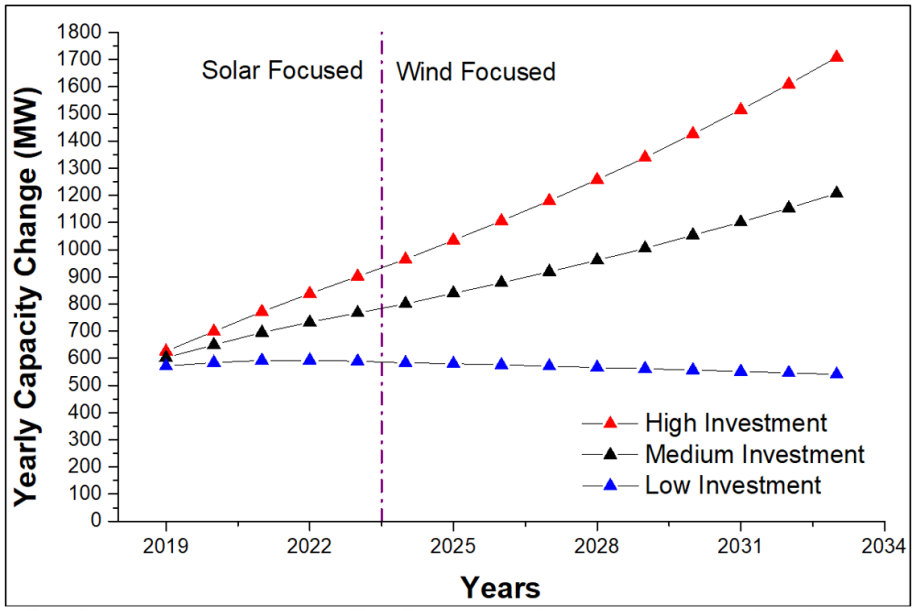


Figure 3.14 Yearly capacity changes of renewable energy sector in Turkey for optimum investment scenario

Thus, by the year 2033, the capacity of solar energy may increase by 49%, 58%, or 63% and the capacity of wind energy may increase by 74%, 131%, or 173% with respect to the low, medium, and high investment scenarios. The resulting renewable electricity capacity of Turkey in 2033 is illustrated in Figure 3.15.

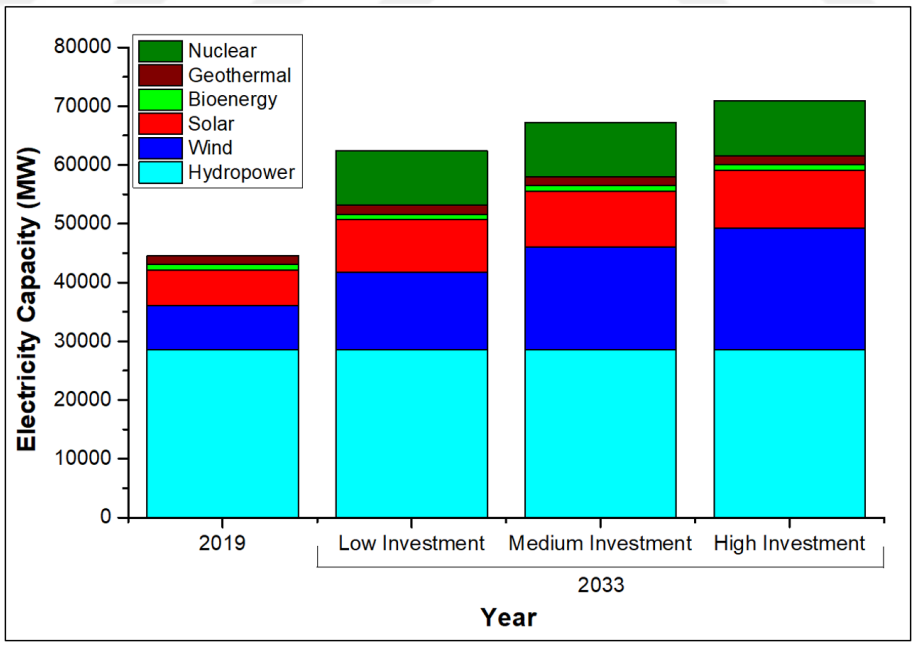


Figure 3.15 Turkey's renewable electricity capacity by the end of 2033 with respect to the investment scenarios, for optimum investment scenario

3.3.4 Turkey's Renewable Energy Shares by 2033

As a result, considering all the investment scenarios, the renewable energy shares are computed for Turkey by 2033. The obtained values to today is represented in the following Table 3.2, with the predominant renewable energy shares in Turkey.

In a free-market economy, optimum investment scenario is likely to take place. Thus, if we consider the medium investment plan at this scenario, we see that renewable energy share of onshore and solar PV wind may increase from 17%, and 13%, to 26% and 14%, respectively, even considering the effects of additional planned nuclear capacity increases. Thus, 26% and 14% are reasonable onshore wind and solar PV renewable energy share targets for Turkey in 2033. However, we see that shares of 35% onshore wind or 31% solar PV are also attainable with focused high investment scenarios. Thus, these values may be set for rather ambitious targets for 2033 as well.

Table 3.2 Turkey's renewable energy shares in 2033 according to the simulated investment scenarios

Scenario:		**100% Ons. Wind Inv. Sc.**			**100% Solar PV Inv. Sc.**			**Optimum Inv. Scenario**		
Year:	**2019**	**2033**			**2033**			**2033**		
Scenario:	**Actual**	***Low Inv.***	***Medium Inv.***	***High Inv.***	***Low Inv.***	***Medium Inv.***	***High Inv.***	***Low Inv.***	***Medium Inv.***	***High Inv.***
Onshore Wind	17%	26%	31%	35%	12%	11%	11%	21%	26%	29%
Solar PV	13%	10%	9%	8%	23%	28%	31%	14%	14%	14%
Hydro power	64%	46%	42%	40%	46%	43%	41%	46%	42%	40%
Nuclear	0%	15%	14%	13%	15%	14%	13%	15%	14%	13%

3.4 Conclusion

In this study, LCOE projections for renewable energy technologies are conducted. It is seen that by 2033, grid parity will be reached for all renewable sources. The LCOE of solar PV, CSP, onshore wind, and offshore wind will continue to decrease in the next decade. LCOE of well-developed technologies such as hydropower, geothermal, and bioenergy are likely to stay stable at the lower limit of fossil fuel technologies, preserving their economic advantages.

In addition, we have presented linear relationships between LCOE and TCI values to be sufficiently used in macro-economic analysis. By using the obtained equations, researchers may obtain LCOE directly from TCI, without needing any external variables such as operating and maintenance costs, land prices, insurance costs, discount rate, tracking factor, annual degradation, fuel expenditures etc. The obtained LCOE value can be referred as "LCOE of an average project for specified TCI", which allows specific project comparison with the world average. The defined economical factor f, explained above, enumerates this comparison.

By using the obtained projections and relationships, we have simulated Turkey's renewable energy investments until 2033, using three different scenarios based on the previous years. We have focused on onshore wind and solar PV, since Turkey has already utilized most of its hydropower, and the renewable investments in the last years are mainly in these sectors [47]. We have presented three approaches in investments: onshore wind focused, solar PV focused, and optimum. It is seen that even with low investment plan, Turkey may increase its renewable energy capacity 500 MW per annum. According to the optimum scenario, which is likely to take place in a free-market environment, Turkey may increase solar PV capacity by 63% and onshore wind capacity by 173%, with high investment plan. With respect to the medium investment plan, Turkey may increase the renewable energy share of onshore and solar PV wind from 17%, and 13%, to 26% and 14%, respectively, including the two nuclear central will be added the total capacity. Hence, 26% and 14% are achievable onshore wind and solar PV renewable energy share targets for Turkey in 2033.

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PUBLICATIONS FROM THE THESIS

Conference Papers

1. M.A. Insel and H. Sadikoglu and M. Melikoglu, "Cost Analysis of Renewable Energy Technologies", Proceedings Book of Fifth International Conference on Advences in Mechanical Engineering, İstanbul, Türkiye, 17 - 19 December 2019, ss.1426