A framework for water and carbon footprint analysis of national electricity production scenarios

Mohammad A. Shaikh [a], Murat Kucukvar [a, *], Nuri Cihat Onat [a, c], Gokhan Kirkil [b]

[a] Department of Industrial Engineering, Istanbul Sehir University, Orhantepe Mahallesi, Turgut Özal Bulvarı, No: 21, Dragos, Kartal, İstanbul, 34865, Turkey
[b] Industrial Engineering Department, Kadir Has University, Istanbul, 34083, Turkey
[c] School of Sustainability, Julie Ann Wrigley Global Institute of Sustainability, Arizona State University, Tempe, AZ 85281, USA

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ABSTRACT

While carbon footprint reduction potential and energy security aspects of renewable and non-renewable resources are widely considered in energy policy, their effects on water resources are mostly overlooked. This research aims to develop a framework for water and carbon footprint analysis to estimate the current and future trends of water consumption and withdrawal by electricity production sectors for national energy development plans — alongside carbon emissions from various electricity sources. With this motivation, the Turkish electric power industry is selected as a case study and a decision support tool is developed to determine the water consumption, withdrawal and carbon emissions from energy mixes under three different scenarios, namely Business-As-Usual (BAU), Official Governmental Plan (OGP), and Renewable Energy-Focused Development Plan (REFDP). The results indicate that water is used substantially even by renewable resources, such as hydroelectricity and biomass, which are generally considered to be more environmental friendly than other energy sources. The average water consumption of the OGP energy mix in 2030 is estimated to be about 8.1% and 9.6% less than that of the BAU and REFDP scenarios, respectively. On the other hand, it is found that the water withdrawal of the energy mix in 2030 under the REFDP scenario is about 46.3% and 16.9% less than that of BAU and OGP scenarios. Carbon emissions from BAU are projected to be 24% higher than OGP and 39% higher than REFDP in 2030. Carbon emissions and water usage are strongly correlated in BAU scenario as compared with OGP and REFDP, thus carbon friendly energy sources will result in fewer water consumptions and withdrawals, particularly under REFDP.

1. Introduction

According to the United Nations Development Program (UNDP) Human Development Report [1], every continent is expected to be hit by water scarcity. Around one-fifth of the world's population is directly affected by water shortage and 500 million people are at risk of it [2]. Electric power generation can cause substantial greenhouse gas (GHG) emissions as well as water consumption and withdrawals. Although GHG emissions due to electric power generation is extensively studied, its impacts on water resources have been overlooked. Majority of the power plants use fresh water, which is already a scare resource [3]. The energy sector is vulnerable to water resource availability as substantial water is required by both fossil and renewable energy sources [4]. This water requirement is in the form of water consumption and water withdrawal and must be considered when studying the environmental impacts of energy generation and in finding a pathway for controlling, and minimizing the environmental damages of development [5]. Measures to optimize the usage of global water resources are also in order when framing new policies and setting goals [6].

Water shortage and Greenhouse Gas (GHG) emissions are global concerns and serious threats to human security [7,8]. More than 50% of the world's population is expected to live in water scarce areas in the next 50 years [9]. Due to an increase in energy demand/supply as well as a rise in the adoption of water-intensive energy sources such as bio-fuels, a rise of 85%, from the current water usage, is expected in water usage for energy production until 2025 [10]. On the other hand, water is expected to become scarcer in the future because of the increase in the demand for food, energy and

* Corresponding author.
E-mail address: muratkucukvar@sehir.edu.tr (M. Kucukvar).

water associated with the projected population increase. By 2050, overall increase in water use is expected to be between 62% and 76% [11]. Furthermore, Carbon Dioxide (CO_2) is the basic constituent of GHGs, accountable for more than 60% of greenhouse effect and resulting in unusual changes in global temperatures [12–15]. GHGs are the biggest contributor in global warming [16]. Power plants alone contribute to over 40% global anthropogenic CO_2 emissions [17]. Global mean temperature is on the rise with respect to pre-industrialization and if measured to curb the emission of GHGs are not taken, the average mean temperature of Earth is expected to go up to 5 °C by the end of this century [18]. Based on our current practices of carbon emissions, average global temperatures are expected to increase to up to 1.3 °C as compared to the temperatures before industrial revolution [19]. The adverse effects of extensive emissions of GHGs are already evident in terms of rising sea levels, unusual variations in temperatures and rain cycles [20]. Unless concrete steps are taken at regional and global levels to cope with water scarcity and environmental degradation, human development cannot continue at the expected rate [21,22].

Turkey, which is situated at a strategic location of Asia and Europe, is going through a dynamic transformation resulting in excessive consumption of its water resources. Total energy consumption increased by 117% from 1990 to 2000 and by 92.2% from 2000 to 2013 in conjunction with the rapid growth of the industrial, transportation and service sectors in Turkey [23]. Following the restructuring of country's electricity sector that initiated in 1980s, both consumption and generation of electricity have experienced a dramatic change [24]. The changes in the electricity mix of Turkey between 1990 and 2013 are presented in Fig. S1 (in supporting information file). Fossil sources such as coal and natural gas have the largest share of Turkish electricity supply mix. Natural gas accounts for more than half of all fossil fuel-fired generation. Hydropower production is dominant renewable energy source. Biomass, geothermal and solar PV were adopted by the Turkey's electricity sector in 2007 and have grown at a steady pace ever since. The Turkish government plans to increase the share of nuclear power, wind and solar energy in its energy supply portfolio in the future [25].

Turkey's electricity consumption was doubled between 2001 and 2014. Fig. S2 (in supporting information file) shows the annual trend of total energy consumption by the residential (households) and non-residential (industrial, commercial, service, transportation, agriculture, fishing, etc.) sectors. Turkey is perceived to be rich in fresh water resources when compared to the other countries in the region. The country is situated in a semi-arid region and has only one-fifth of the water available per capita of water rich regions like North America and Western Europe. Turkey has annual 1500 cubic meters water per capita which is well below 10,000 cubic meters water per capita considered for water rich countries [26]. The per capita energy consumption in Turkey is just 16% of that of the European Union's average. Nevertheless, Turkey's energy consumption is increasing steeply because of the fast-paced industrialization and urbanization. Turkey is not an oil-rich or a massive natural gas producer, like some of its neighbors. Thus, it has tried to meet its major energy needs through the locally available coal resources and hydropower as well as imported natural gas. The government plans to meet its rising energy demand through sources that will require water for electricity production [26,27]. Although, several sustainability assessments have focused on Turkey's electrical sector [28–31], no comprehensive study has yet been performed on the water impacts of Turkey's electricity generation. Thus, this study is an initial effort to help optimize the use of water resources in Turkey's power generation sectors and to providing the Turkish policy makers with information on the water use of alternative energy mixes to meet the future energy demand.

Water and energy generation are strongly related with each other [32]. Therefore, to effectively control and curtail the water usage in electricity production, it is necessary to reliably account for water usage in the energy generation process [33]. Madani and Khatami [34] reviewed various indices that have been used in the literature to evaluate the impact of energy production on water resources. According to their review, water consumption refers to the amount of fresh water actually consumed in the process of producing electricity. This water gets out of the system and becomes unavailable for the other uses. Water consumption can occur in the form of evaporation of water from the reservoirs, mixing the water with effluents, spilling it in sea, or through any other process which makes the water unusable at the end of the process [34]. Water withdrawal, however, is the amount of water withdrawn from water sources (e.g. reservoirs and rivers), which is mostly used for cooling purposes and is returned to the system at the end of the energy production process [35].

Power plants, particularly fossil fueled plants, contribute substantially to the carbon emissions. In China alone, 48% of the total carbon emissions stemmed from electricity generation through fossil fuel as of 2010 [36]. Coal fired power plants emit the maximum GHG emissions followed by liquid fuel oil and natural gas power plants,, respectively. Importantly, renewable energy sources like hydroelectric, biomass, solar and geothermal also leave carbon footprint as they are utilized for energy generation – hence, they are not completely green energy sources.

This research aims to present a framework assessing water and carbon footprints for national energy development plans, by presenting a spreadsheet model analyzing the water consumption and withdrawal as well as carbon emissions from all the energy sources. The developed model can serve as a decision support tool to aid policy makers take decisions about electricity generation sources with a good understanding of the implications of their decisions for a nation's water resources and environmental policies. As a case study, a scenario analysis is conducted to estimate the water consumption, withdrawal, and carbon emissions associated with Turkish Government's energy plans until 2030. Fig. S3 in supplementary file shows the forecasted rising energy consumption in Turkey until 2030. Turkey's electricity needs will almost double, nearly 95% increase, until 2030 compared to 2015 levels, which will put additional stress on water resources and can cause significantly more GHG emissions. So we have to find a best energy generation mix of energy sources to keep the country's water usage and carbon emissions under the critical levels.

In the following sections of this paper, the methodology of this study is defined and the data collection methods are discussed. This is followed by a scenario analysis of Turkish energy mix. Finally, the results are incorporated into a decision support tool to provide a generalized view of water usages and GHG emissions of different energy mixes and help optimizing the country's water and carbon footprint. Policy implications are discussed and then paper is concluded by presenting the key findings of this study.

2. Methods

The electricity consumption data is obtained from the International Energy Agency (IEA) [37] and Turkish Statistical Institute [38]. Using autoregressive integrated moving average (ARIMA), the electricity consumption data is forecasted fort the analysis period. The method employed for doing scenario based energy water analysis involves four primary segments, as shown in Fig. 1 [39]. The Electricity production in Turkey is studies with respect to individual energy sectors available in the country from 1990 to 2013. A large portion of this data is obtained from the database of International Energy Agency. Over this 23 years' span, it is revealed
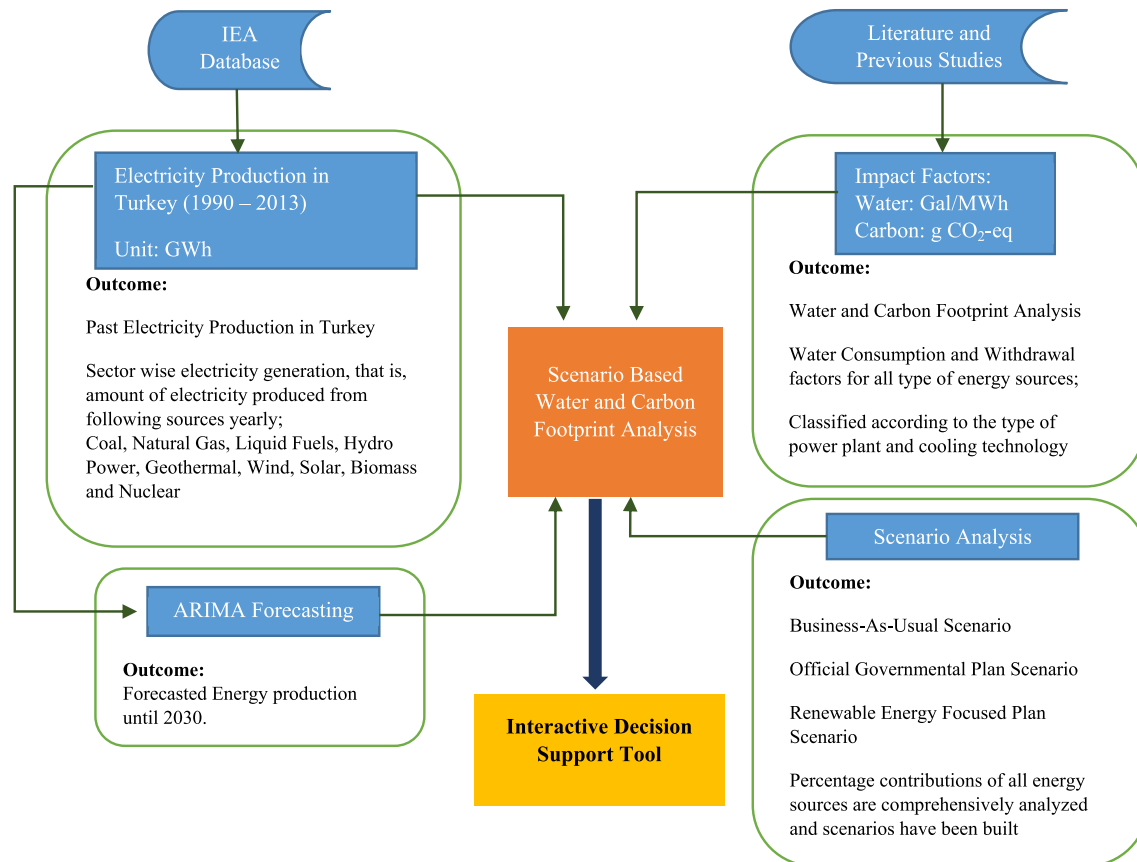
Fig. 1. Method.

that Coal, Natural Gas and Hydropower are the most dominant sources of electricity in the country. Liquid fuels, on the other hand, have never been a major source of energy. Wind, solar and geothermal energy sectors grew after 2003 and are still in their developing stage. The Auto Regressive Integrated Moving Average (ARIMA) forecasting tool is used to forecast the energy production in Turkey, keeping in view the socio-economic factors, population growth, regional and climatic changes until 2030.

Water consumption and water withdrawal rates of all the energy sources are extensively studied in the next phase. For energy sector, water usage is highly dependent of the type of cooling system used. Therefore, this paper considers the most commonly used cooling systems for each energy source and their water usage rates are shown in terms of the range of minimum, mean and maximum amount of water usage that is expected to happen over the coming years. Carbon emissions from power plants are quantified based on the capacity factors, life cycle assessments, productivity and cooling systems. For each energy source, corresponding equivalent carbon emissions per kilowatt-hour (kWh) are quantified based on thorough literature review discussed in section 2.1.

In scenario analysis, different policy options for Turkey are comprehensively considered. Three scenarios are formulated, namely: Business as Usual, Official Governmental Plan and Renewable Energy focused Development Plan. For each scenario, relevant conditions are analyzed and the growth of each energy sector is studies over the time lapse of 5 years until 2030. Percentage contributions of every source combined with the total electricity forecast and water consumption and water withdrawal factors are all fused to analyze energy water nexus in Turkey. In

order to make our study more interactive and useful for policy makers, a decision support tool is also developed with interactive capabilities. Further details on the interactive decision support tool are given in the following sections and its access link is given in the appendix.

There are four main assumptions in this study:

1. Electrical consumption is assumed to increase based on the ARIMA forecasting until 2030. The results of ARIMA have been compared with the available sources and are found to be comparative.
2. Electrical sectors share in overall energy production are based on past studies referred in earlier sections. In order to make it realistic, interactive system has been designed to make this model realistic.
3. Water factors, that is, unit water consumption and withdrawal values per electrical energy produced are taken in a range of minimum and maximum values because water consumption and withdrawal depends on several variables such as cooling system used in power plants, their efficiency, operating conditions and many more. Therefore, mean values of the ranges are used as a basis of our results.
4. GHG emission coefficients from different power generation sources quantified are considered to remain same over the period of analysis considered in this study.

2.1. Data collection

To analyze water usage from energy sector in Turkey, following

records were obtained from the available sources: total energy consumed in annual basis, a share of individual energy source in total energy consumption, proportions of electricity used by residential and non-residential sector in Turkey. Year 1990 was set as the base year for this study and 2014 is the most recent year for this study. The ARIMA forecasting method was then used to forecast the values until 2030. Total energy consumed and energy sector wise production on annual basis is summarized in Appendix Table 1.

As Fig. S3 in supporting information file showed how the energy consumption (in Gigawatt- Hours) has varied over the years. Fig. 2(a) shows the trend of percentage increase in the energy consumption with respect to the previous year. As it is apparent, there is a mix trend in the increase in energy consumption from year to year. However, comparing the increment from the base year, i.e. from 1990, energy consumption is increasing at a very rapid rate. The trend of energy consumption growth from 1990 is shown in Fig. 2(b). Demand for electrical energy in Turkey doubled in 1999; with increasing population and rapid industrialization, energy consumption grew to about 206% in 2006. This sharp increase in trend continues as energy consumption increased about 338% in 2013 compared to 1990.

To meet a steep rise in the energy requirements presented in Fig. 2(b), energy sector has growth at a rapid pace as well – utilizing different energy sources to generate electricity. Coal, liquid fuels, natural gas and hydro power plants are the major contributors in the Turkish electricity generation. Other sources such as biomass and geothermal have been in existence since long, but their production volumes are not comparative. Wind energy and Solar PV have started to take roots in the country and are expected to grow with increasing environmental concerns.

Coal is a prime contributor in the generation of electricity. Shares of liquid fuels are relatively less, and declining trend is observed as the factual values move towards 2013. Natural Gas fired power plants also dominate despite that the country depends largely on its import of Natural gas from other countries; which is an added burden on its economy as well [29]. Other renewable sources such as wind, solar photovoltaic (PV), geothermal and biomass are growing steadily at a normal pace. It is worth to mention that Turkey is among the few countries where geothermal technology is deployed to produce electricity [40].

To access the amount of water withdrawn and consumed from different power sources, each source is studied for its own water consumption and withdrawal factors. Water usage levels for power plants depends on more than one elements: design of power plant, type of fuel used, cooling system technology [41]. Therefore, data ranges are used to propose the range of water consumed and withdrawn by power sectors where necessary. Water utilization in life cycle of almost all the energy sectors happen in their operational phase; except for non-thermal renewable source [42]. Thus, water used in operation of power sectors considers cooling systems, washing purposes and other auxiliary processes [41]. Regardless, the cooling system is the actual element determining the water utilization of a power sector [43]. Table S1 in Appendix shows the water consumption factors, in gallons per megawatt

hours, by individual energy sectors based on the type of cooling system and technology used. Similarly, Table S2 given in appendix shows the water withdrawal factors from individual energy sources according to the relevant cooling systems and technology. Graphical representation of water consumption and withdrawals are presented in Figs. S4 & S5 shown in the supporting information file.

GHG emission factors or carbon coefficient of power generation sources are also considered to analyze environmental impacts resulting from power sources of various types. For every power generation source, detailed examination of the factors like capacity factor, technology type, life cycle assessment, cooling technologies and other related factors is done along with their corresponding effects on the eventual carbon emissions from former literature and reports. For example, National Renewable Energy Laboratory (NREL) report on the "life cycle assessments of coal-fired power production" and "Life Cycle Assessment of a Natural Gas Combined-Cycle Power Generation System" quantified the contributions of GHGs by coal and natural gas combined power plants respectively [44,45]. Hiroki Hondo [46] has done a comprehensive study of greenhouse gas emissions from coal, natural gas, hydroelectric, nuclear, wind, solar and geothermal power plants in relation to global warming. White and Kulcinski [47], Odeh and Cockerill [48], Meier [49] and various other researchers [50–52] have extensively studied the emissions from different power generation sources and their work is used in this study to predict the carbon emissions from the respective power sources in Turkey. Fig. 3 shows the Pareto diagram of the average GHG emissions by all the power sources present in Turkey. Coal, liquid fuel and natural gas fueled power plants constitute to 90% among the overall carbon emission factors, in terms of grams per kilowatt-hour. Although solar energy and geothermal energy are assumed to be renewable having no carbon emissions, but we have found out that their average greenhouse gas emission factors are about 50 g CO_2-eq/kWh and 34 g CO_2-eq/kWh respectively [53,54]. Extraction of energy from waste, as in the case of electricity generation from biomass, contributes to GHG emissions as well and happen to emit about 32 g CO_2-eq/kWh [55].

On the other hand, values of the water usage factors by energy sources are presented in terms of volume per unit electrical output (gallons per Megawatt-hours). They are further categorized as the minimum amount of water used, mean amount of water used and the maximum amount of water used by each type of cooling technology. The amount of water used by a power plant will lie between the minimum and maximum value, depending on the source, cooling method and technology. This paper considers the minimum amount of water, the range of mean amount of water that a power plant may use and the maximum level of water that any source can use while producing the required electricity. As there are many cooling technologies associated with energy sectors, mean factors are bifurcated as the lower mean and upper mean, suggesting the minimum and maximum value among the mean values of all the cooling technologies of a specific energy sector. The reason for making a range of mean in each energy source is to depict the average water usage by each sector irrespective of their cooling technology. In case where there is one cooling system, the range of mean is not applicable.

Water consumption factors diversely vary from sector to sector [56]. Generic technology in tower cooled coal fired plants consume most water in Coal sector, followed by subcritical and supercritical technologies; having maximum consumption factors of 1100 gallons per megawatt-hour, 942 gallons per megawatt-hour and 846 MW-hour, respectively. Water consumption factor in Liquid fuels and hydropower sectors vary from 300 gallons per megawatt-hour to 480 gallons per megawatt-hour and 1425 gallons per megawatt-hour to 18000 gallons per megawatt-hour, respectively.

Table 1
Water consumption and withdrawal comparison.

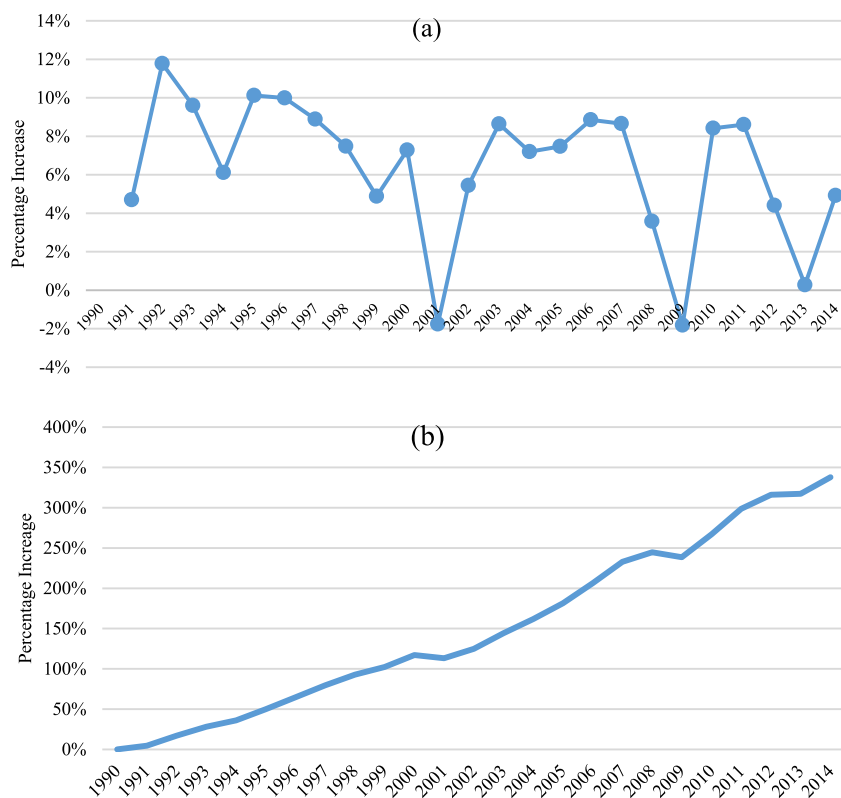| Year	Total water consumption (Gallons)			Total water consumption (Gallons)		
	S1	S2	S3	S1	S2	S3
2015	3.92E+11	3.92E+11	3.92E+11	3.18E+12	3.18E+12	3.18E+12
2020	5.04E+11	5.15E+11	5.10E+11	3.46E+12	3.34E+12	3.16E+12
2025	6.06E+11	6.09E+11	6.14E+11	4.09E+12	3.75E+12	3.23E+12
2030	6.67E+11	6.17E+11	6.76E+11	5.21E+12	4.16E+12	3.56E+12

Fig. 2. (a) Electricity consumption trend (1990–2014) with respect to previous year. (b) Percentage increase in electricity consumption since 1990.
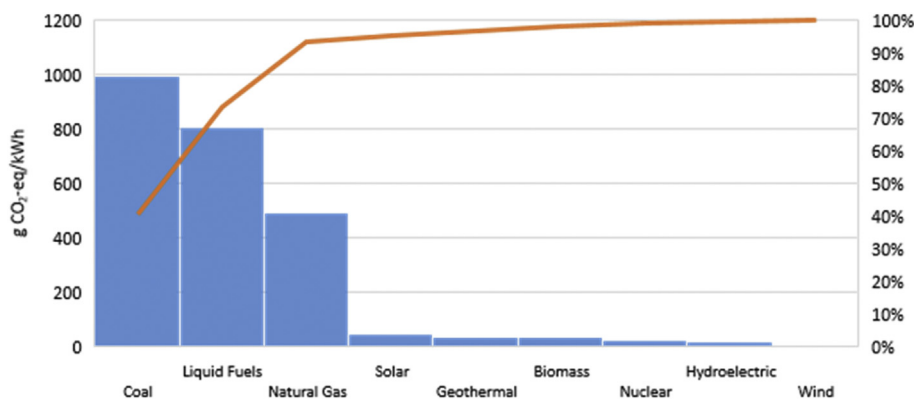

Fig. 3. The average GHG emissions by energy sources.

Natural gas power plants, as well as biomass power plants, which use steam to as a driver for turbine rotation, consume maximum water among other technologies. Enhanced Geothermal Systems (EGS) dominates geothermal technologies. Generic nuclear power plants having tower cooling system consume most water out of generic plants having once-through cooling system and pond cooling system. Hydropower sector, despite being a non-fossil based-renewable energy, happen to consume maximum volume of water among rest of the sources, largely because of the evaporations from exposed water surfaces of large reservoirs of dams and lakes [57].

Water withdrawal factors, on the other hand, lie on the higher side as compared to water consumption. This is due to the intensive water withdrawals for cooling purposes in coal, liquid fuels, natural gas, biomass and most importantly, nuclear energy sector. As in the case of water consumption, cooling technology has a substantial role to play as far as water withdrawals are also concerned.

Once-through cooled generic coal power plants withdraw most water out of all the cooling technologies and technologies of coal energy sector considered in this study. The highest water withdrawals factors for coal power production range from 20,000 gallons per megawatt-hour to 50,000 gallons per megawatt-hour. Natural gas designed on combined cycle power plants and steam withdraws most of the water, with steam plants dominating like they dominated in water consumption. Combined cycle plants withdraw minimum of 11,380 gallons per megawatt-hour to the maximum limit of 20,000 gallons per megawatt-hour while gas plants using steam withdraws 10,000 gallons per megawatt-hour to 60,000 gallons per megawatt-hour. Water withdrawal factors in geothermal power sector have minimum ranges between

220 gallons per megawatt-hour to 290 gallons per megawatt-hour and maximum range between 630 gallons per megawatt-hour to 720 gallons per megawatt-hour. Biomass and nuclear are thought to be environmental friendly power options, but they also withdraw considerable volumes of water. Biomass plants with steam technology and once-through cooling system withdraws 20,000 gallons per megawatt-hour to 50,000 gallons per megawatt-hour and generic nuclear plants with once-through cooling withdraws 25,000 gallons per megawatt-hour to 60,000 gallons per megawatt-hour. Solar photovoltaic (PV) energy sector withdraws as low as 0 gallons per megawatt-hour to 1600 gallons per megawatt-hour. However, mean water withdrawal in solar PV is also close to 0 gallons per megawatt-hour. Wind energy withdraws no water; therefore, it is the least water dependent source as far as water withdrawal is concerned. Hydropower water withdrawal factors of run-of-the river hydropower plants are not considered in this study due to the fact that these power plants are generally located in between the natural flow of the river and do not take away water from other purposes like agriculture, industrial and domestic purposes for a long period of time.

Above discussed GHG emission factors, water consumption and withdrawal factors will be used as a tool to calculate the equivalent grams of CO_2 emissions together with the volumes of water consumed and withdrawn in Turkey over the years and also, to predict the amount of water that will be consumed and withdrawn in the future years.

From carbon emission factors, water consumption and withdrawal factors, sector wise water utilization is calculated by:

$$WC_{xy} = WCf_x * EC_{xy} * 1000 \qquad (1)$$

$$WW_{xy} = WWf_x * EC_{xy} * 1000 \qquad (2)$$

$$CE_{xy} = Cf_x * EC_{xy} \qquad (3)$$
where,

WC = Water Consumption;
WCf = Water Consumption Factor;
WW = Water Withdrawal;
WWf = Water Withdrawal Factor;
CE = Carbon Emissions;
EC = Energy Consumed;
x = Energy sector;
y = Year of study;
WC_{xy} = Water Consumption of x Energy sector in Year y;
WCf_x = Water Consumption Factor of x Energy sector;
WW_{xy} = Water Withdrawal of x Energy sector in Year y;
WWf_x = Water Withdrawal Factor of x Energy sector;
CE_{xy} = Carbon Emission of x Energy sector in Year y;
Cf_x = Carbon Emission Factor of x Energy sector;
EC_{xy} = Energy Consumed by x sector in Year y;

Units of water consumption and water withdrawal factors are gallons per megawatt hours (Gal/MWh) and unit of energy consumed is gigawatt hours (GWh). Hence, to homogenize the units, both eqn. (1) and eqn. (2) are multiplied by 1000. Similarly, units of carbon emission factors are grams of CO_2 and equivalent gasses per kilowatt-hour (g CO_2-eq/kWh) while units of energy consumed is GWh.

Total water consumption and withdrawal volumes for the year are calculated by using:

$$WC_y = \sum_{x=0}^{n} WC_{xy} \qquad (4)$$

$$WW_y = \sum_{x=0}^{n} WW_{xy} \qquad (5)$$

$$CE_y = \sum_{x=0}^{n} CE_{xy} \qquad (6)$$

2.2. Energy-based analysis

In this section, a general overview of Turkey's energy sources used for electricity generation is discussed. Their proportions in overall electricity production have been studies and analyzed from 1990 to 2013. Based on this analysis and external factors, their future developments have been predicted through scenario analysis discussed in coming sections.

Demand for electricity in Turkey is going through a rapid change [58] largely due to the surge in sectoral growth in the country. From 2004 to 2014, electricity demand has increased by 70% and in expected to grow at the same pace. Turkey's economy performance, technological advancements, amount of imports and exports, GDP growth and lifestyles of the people have considerably burdened the energy sector [59]. In order to meet these increasing needs, Turkish energy sector is largely dependent on fossil fueled power plants, particularly coal and natural gas. Therefore, Turkish government has not only to meet the ever-increasing power demand, but also to reduce its reliance on imports of energy and energy fuels.

Turkey's share of natural energy resources in terms of world reserves are very limited, therefore, more than 52% of Turkey's energy requirements are met through fuel imports [60], and sharp increase in electricity demands have increased the country's inclination to rely more on importing energy fuels and supplies [30]. Turkey's primary energy sources are coal, liquid fuels, hydropower, natural gas, geothermal energy, solar energy and biomass. The country produced about 44% of its electricity from gas, 24.8% electricity from coal, 25.2% from hydro, and rest from wind, geothermal, biomass and solar in 2014. The government is expecting the electricity demand to increase by 100% from 2014 to 2023.

29% of global energy demand come from coal, which result in 44% of global CO_2 emissions [61]. In turkey also, as it can be seen from Fig. 4, coal and natural gas has been dominant in Turkish electrical sector. Hydropower also is one of the major contributors. Turkey imports most of its natural gas; even then, natural gas fired power production surged after 1998 and continues to vary in between 42% and 50% in the following years. Coal energy, on the other hand, slightly declined below 30% in 2001, but it is a major contributor in overall production. Contribution from liquid fuels is not very considerable since long and its rate is declining as other renewable technologies are taking their roots. Wind energy comes on surface in later 2007 and is growing steadily since then. In 2013, 3.1% of total energy requirements were supplied through wind energy.

2.3. Scenario analysis and scenario building

The primary motivation behind a scenario analysis is a target in mind or a goal that constitutes in the development of scenarios and to predict the results of future, based on the preset assumptions or
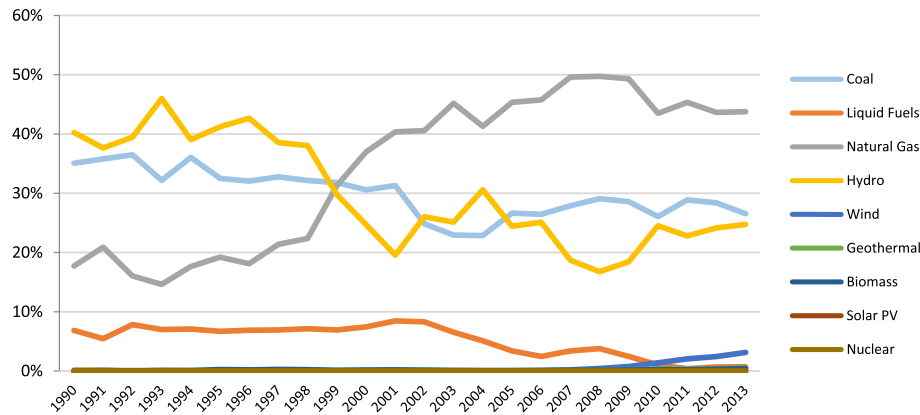
Fig. 4. Turkey Electricity generation mix (1990–2013).

goals. Since long, scenarios are used for discovering the forthcoming progress under a set of assumed conditions; especially in decision support in energy sectors [62]. This method of analysis gives the alternative options of how our subject of research will unfold.

In order to understand systems well, we need to evaluate their models through playing with the strings and constraints and then, by observing their behavior and responses, we tend to determine their likely future states. Unfortunately, this method is useful with non-sophisticated and certain systems. Real world systems, studying on energy sector in our case, is a very complex system whose sectors are so independently dependent of diverse factors that it is impossible to accurately predict their behavior. So judgmental tools are only used as experimental basis. Therefore, scenarios simplify this gap of our understanding about the working, behavior and evolution of complex systems. This is generally done by attaching quantitative narrative strings of the future with quantitative respective elements. This makes scenarios a useful tool for scientific assessments and for learning systems. Also, they enables the policy makers to analyze the system from multi dimensions before coming up to a decision [63]. Hence, they happen to be one of the main methods for solving the complexities and uncertainties associated in long term policy making by establishing the logical boundaries [64].

Scenario analysis for environmental and energy sectors have been done at different scales; ranging from worldwide long-term international scenarios to local mid-term scenarios (Georgopoulou et al. (2009)). In this study, to analyze the water usages under different energy mixes of energy sectors, scenario analysis is therefore deployed as a productive tool to better understand and interpolate the volumes of water that will be used in Turkey in coming years. All the electricity producing sectors of Turkey are studied in detail keeping in view their contributions in the total electricity consumptions of the country, their future perspectives in line with the governmental policies, their environmental impacts and socio-economic repercussions and their driving fuel availability.

Once the trends of energy mixes of different sectors are established, water consumption and withdrawal factors, presented in earlier sections, are used to calculate the amount of water consumed and withdrawn annually by each energy source in the country as explained in equations (1) and (2). A decision support tool is developed for policy makers to study the water consumptions and withdrawals from each energy source, as well as collectively, of all the scenarios deployed. Also, developed tool can help them in observing the changes with any other electricity mix. The

tool takes scenario input from user, which is the percentages of the distinct energy sectors in the overall energy sector of the country, and present detailed results of the water consumptions and withdrawals made by individual scenarios and individual energy sources. The user can change the energy mixtures to compare the results of different scenarios.

Turkey, which corresponded to about 1.24% (around 459,102 Mega tons) of emissions equivalent of CO_2 in 2013, became the signatory of The Paris Agreement under United Nations Framework Convention on Climate Change [67]. Therefore, they have pledged to reduce the risks and impacts of climate change by curbing global average temperatures [68]. The government is working on building renewable energy resources, and establishing frameworks to improve technologies to prevent carbon emissions while securing the leakages of electricity in distribution system, which is in line with the COP 21 declarations. Furthermore, international economic institutions have predicted that Turkey's economic growth rates with remain on the higher side which will result in exponential increase in energy consumption as well [69].

To reduce the dependence on import of fuel for electricity, especially natural gas, Turkish government aims to exploit its coal resources for power generation under its plan of "Dash for Coal" [70]. Alongside this, the country is also aiming on long-term energy strategies to speed up its renewable energy consumption. Increasing the percentage mix of renewable energy production will also result in the reduction of shares of coal and natural gas [71]. Hydroelectric power potential has the capacity of meeting 33%–46% of Turkey's electricity demand until 2020 and this share can easily increase to its maximum potential easily and economically until 2030 and further [72].

With increase in renewable energy projects around the world, costs of setting up renewable power energy technologies are decreasing gradually. Turkey, being abundant in renewable energy resources can clinch on this opportunity to cut down the use of imported coal and natural gas in power generation. The key renewable sectors for Turkish energy sector are hydropower, solar photovoltaic, wind, geothermal and nuclear energy [73]. By 2023, around 159,000 GWh of renewable electrical energy is projected to be installed in Turkey [69].

Keeping in view the governmental policies, worldwide technological trends and related factors that can influence electrical energy sector, along with the available studies about the future of Turkish energy sector, thorough analysis of energy sources in Turkey have been conducted and their potential mix have been simulated in three different scenarios until 2030. Percentage contribution of each power source is calculated and then, through

scenario analysis, their mixes are predicted for 2020, 2025 and 2030. Three scenarios have been used: Business-As-Usual (BAU), Official Governmental Plan (OGP) of the government of Turkey based on the future energy projects and their expected deadlines, and the Renewable Energy Development plan (REFDP). After, water consumption and withdrawal are predicted by individual electricity generation source keeping in view their percentage contribution in the Turkish power sector. This resulted in foreseeing the volumes of water that will be required to cater Turkish electricity demands over the years until 2030. According to the Turkish Ministry of Energy and Natural Resources, 36 GW of hydropower electricity, 48 GW of wind energy and 2 GW of geothermal energy capacity is available in the country. While it is estimated that solar energy potential is as much as 380,000 GWh per year and biomass energy potential is about 1300 GWh per year.

2.3.1. Scenario 1 (BAU)

Scenario 1 is the first scenario developed to analyze the trends in growth of different power sectors and their water consumption and withdrawals until 2030. Scenarios have been developed in line with the current trends in the development of energy sectors in Turkey. BAU differs from official governmental plan as it does not consider ambitious projections. In this regard, present conditions of electricity sector and existing policies of Turkish government have been studied along with the projects that are in the process of

completion in the coming times.

Fig. 5 shows the variation of Turkish energy sector mix in BAU scenario from 2015 to 2030. Electricity consumption from coal energy in BAU scenario is expected to increase from 60,740 GWh in 2015 to 100,340 GWh until 2025, with a steady percentage of around 23%–24% in the overall mix. By 2030, this proportion increased to 27%, taking energy production through coal to around 139,000 GWh. Energy production from natural gas resources is expected to decrease substantially as it is evident from the government's commitment of reducing dependency on import of gas and utilizing local coal resources. Natural gas accounts for approximately 44% of the overall energy mix in 2015 are projected to go down to around 23% until 2030 under BAU. This decrease in the percentage is not compatible with the increase in the overall demand; meaning that in 2015, about 116,500 GWh of electricity was produced from natural gas and in 2030, it is projected that 119,711 GWh of electricity will be produced. Amount of electricity produced in 2030 is still greater than its value in 2015. That is because of the overall exponential increase in the energy demand. Renewable energy under Business-*as*-usual scenario also depicts a very interesting trend. Hydropower energy is estimated to fluctuate from 25.8% in 2015 to 27.5% in 2020 to 26.6% in 2025 to 22.8%; while proportions of wind energy are expected to increase steadily, but still at a slow pace as compared to the rest of the world. It is estimated that wind energy proportions will increase from only 4.4%
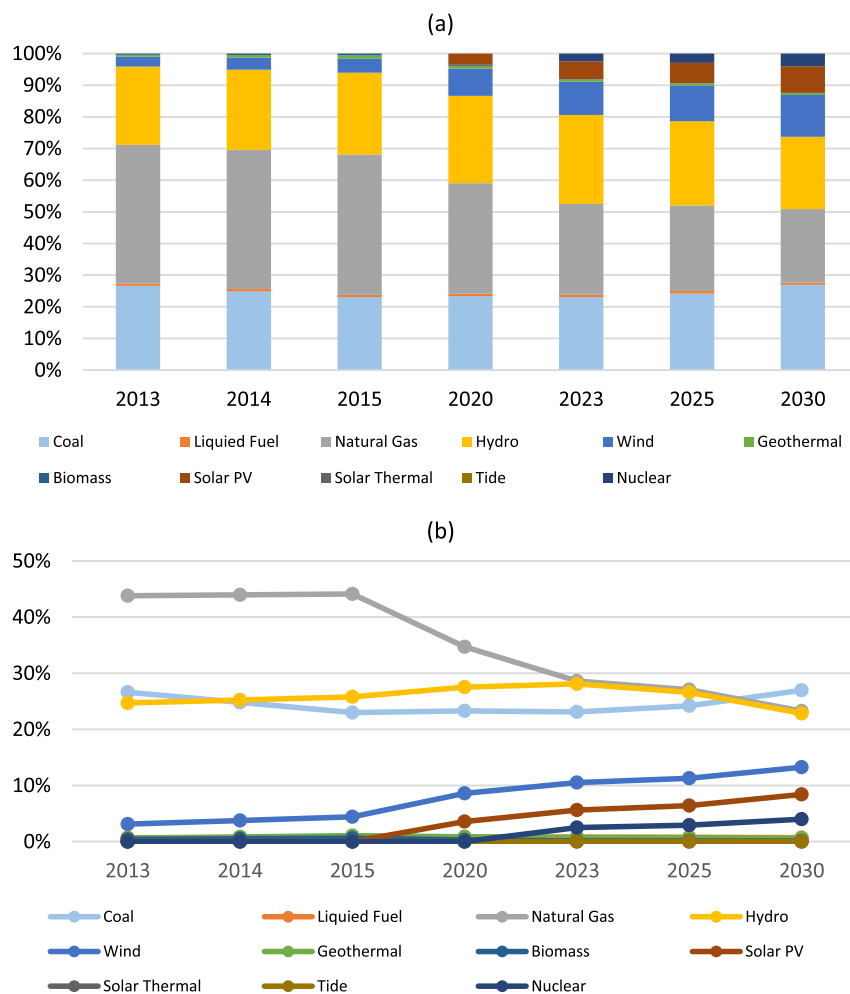
Fig. 5. Scenario 1 (Business-As-Usual) Energy Mix Percentages (2013–2030) **(a)** cumulative stacked representation; **(b)** trend of percentage fluctuation Energy Mix percentages (2013–2030).

having just a share of 11,635 GWh to 13.2% making the share of about 68,000 GWh in 2030. Geothermal and biomass technologies under BAU are expected to stay under 1%, making their share very minimum. Solar photovoltaic (PV) technology in Turkey's BAU scenario is projected to take a heap until 2020. It is estimated that Turkey will be producing 3.6% (around 11,800 GWh) of its electrical energy from solar PV in 2020, 6.4% (26,500 GWh) in 2025 and 8.4% (43,250 GWh) in 2030. Nuclear energy power is expected to come on-line in 2023 and will be contributing 2.5% of the total energy share. The pace of development of nuclear plants in Turkey is expected to remain steady under BAU. Until 2030, 4.7% of the total energy is expected to come from nuclear technology.

2.3.2. Scenario 2 (official governmental plan)

Scenario 2 is based on the targets and timelines of Turkish government's projects to cater growing energy demand in the country. Existing policies to cope up the increasing power demands, capacity planning and current conditions of the electricity market and sector are all considered while formulating the energy mixes for this scenario. Government plans and deadlines along with projected time when future energy projects will come on-line are taken into account in this scenario.

Fig. 6 shows the variation of Turkish energy sector mix in BAU scenario from 2015 to 2030. Official governmental plan suggests that the dependency on coal for energy will continue, however, it

will not be a major player in the country's electricity mix as other renewable sources are expected to grow. Coal energy's contribution will range from 23% to 20.8%−21.2% in 2015, 2025 and 2030 respectively. Natural gas, on the other hand, is expected to have a sharp decline due to the government's diversion towards exploiting local coal resources and building up renewable resources. A share of natural gas is expected to fall from 44% to 15% until 2030.

Wind, solar PV, and nuclear energy development is expected to grow substantially under this scenario. These targets are set in line with the global targets of reducing carbon emitting power dependencies and focusing on renewable energy sources. Wind energy is expected to have 23% share until 2030 in the country's overall electricity mix. Solar PV power production is assumed to grow from 1.6% in 2020 to 2.5% in 2023 to 4.5% in 2025 to 9.7% in 2030. As far as nuclear energy is concerned, the government plans to complete two under construction nuclear power plants by 2023, their projected power contribution to the system will be about 7.9% in 2023 and this proportion is expected to remain stable with the induction of Sinop and Lgenada nuclear projects until 2030 [25].

2.3.3. Scenario 3 (renewable energy focused development plan)

Scenario 3 is the renewable energy focused development plan where the assumptions of Turkish government policies to prioritize renewable electrical options are taken into consideration for the coming decades. Development of coal and natural gas sector will be
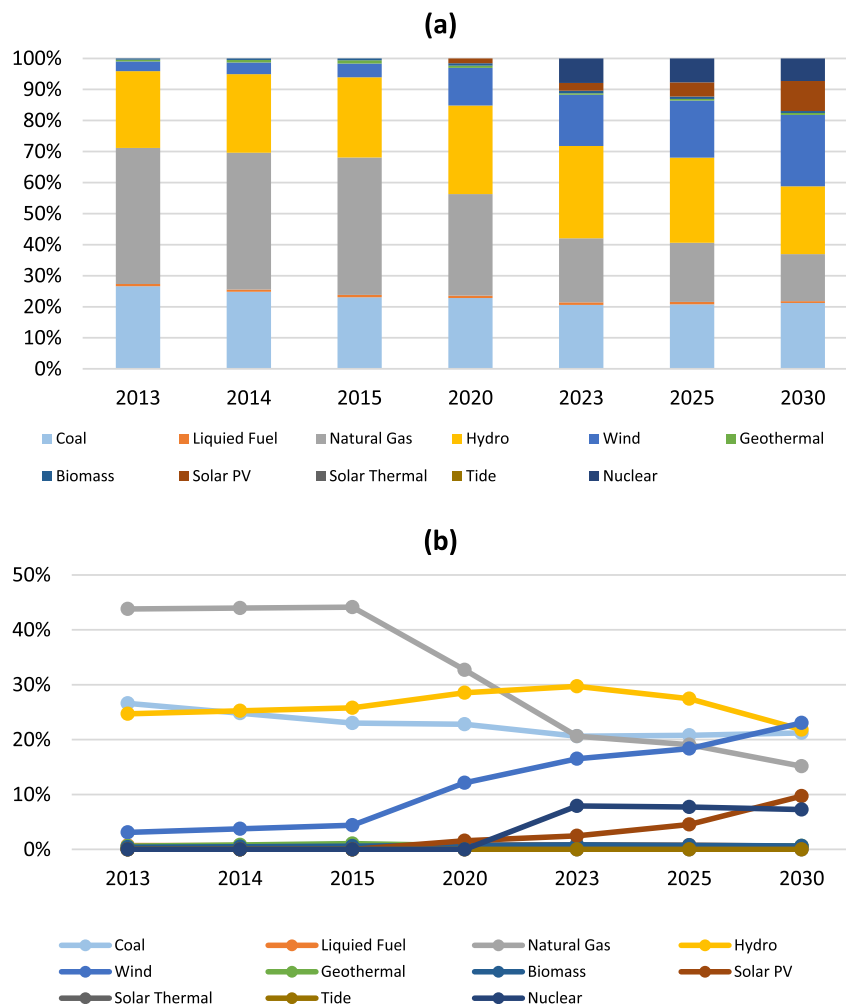

Fig. 6. Scenario 2 (Official Government Plan) Energy Mix Percentages (2013−2030) **(a)** cumulative stacked representation; **(b)** trend of percentage fluctuation Energy Mix percentages (2013−2030).

given less attention as compared to wind and solar photovoltaic (PV) energy, which have not been very dominant in Turkish electrical mix, despite their rapid growth worldwide [69].

Fig. 7 shows the variation of Turkish energy sector mix in BAU scenario from 2015 to 2030. Energy production from fossil fuels is expected to fall substantially. Coal energy is expected to decrease from 23% in 2015 to 19.2% in 2020 to 14.8% in 2025 to 12.1% in 2030. Natural gas is also expected to decrease from 44% in 2015 to 20.6% in 2030. Development of renewable energy technologies are prioritized in this scenario, particularly wind energy and solar PV. In REFDP scenario, wind energy is expected to grow at a rate of about 5%–6% every 5 years; i.e. from 4.4 in 2015, its proportion in overall electricity mix will climb up to 20% in 2030. Development of solar PV will also be also estimated to be on a higher node as compared to the other two scenarios. Solar PV has the potential to cater about 6% of Turkey's electric needs by 2020. This proportion is estimated to be doubled in 2025, as it will get to 12%. In 2030, solar PV contribution will reach to about 17.4%.

3. Results & discussion

The results present water consumption and withdrawal factors, GHG emission factors, scenario analysis and forecasted electricity production. A time-series analysis results covering 2015, 2020, 2025 and 2030 are presented in this section and all the scenarios are showed and discussed alongside each other. Water usage in 2015 is same for all scenarios as 2015 is set as the base year and percentage contribution of all the energy sources is same in all the scenarios for this year. Eqns. (4)–(6) developed in the methods sections are used to calculate the total water consumption and water withdrawal, as well as the total amount of CO_2 emissions for all the scenarios. Amount of water consumed and the amount of water withdrawn are compared separately along side the amount of carbon emissions for each scenario in the following sections.

Firstly, amount of gallons of water consumed and withdrawn as a result of the total electricity production in the country are presented and are categorized by individual power sector. The researchers have driven the percentages from these values and have represented them in separate figures. Then total water consumption, withdrawal and carbon emissions results are shown collectively to give a different illustration of the scenarios for every 5 years until 2030. It is important to mention that the results shown in this paper are largely summarized. Please refer to our decision support tool (see Appendix for link) for detailed results and more insights of analysis.
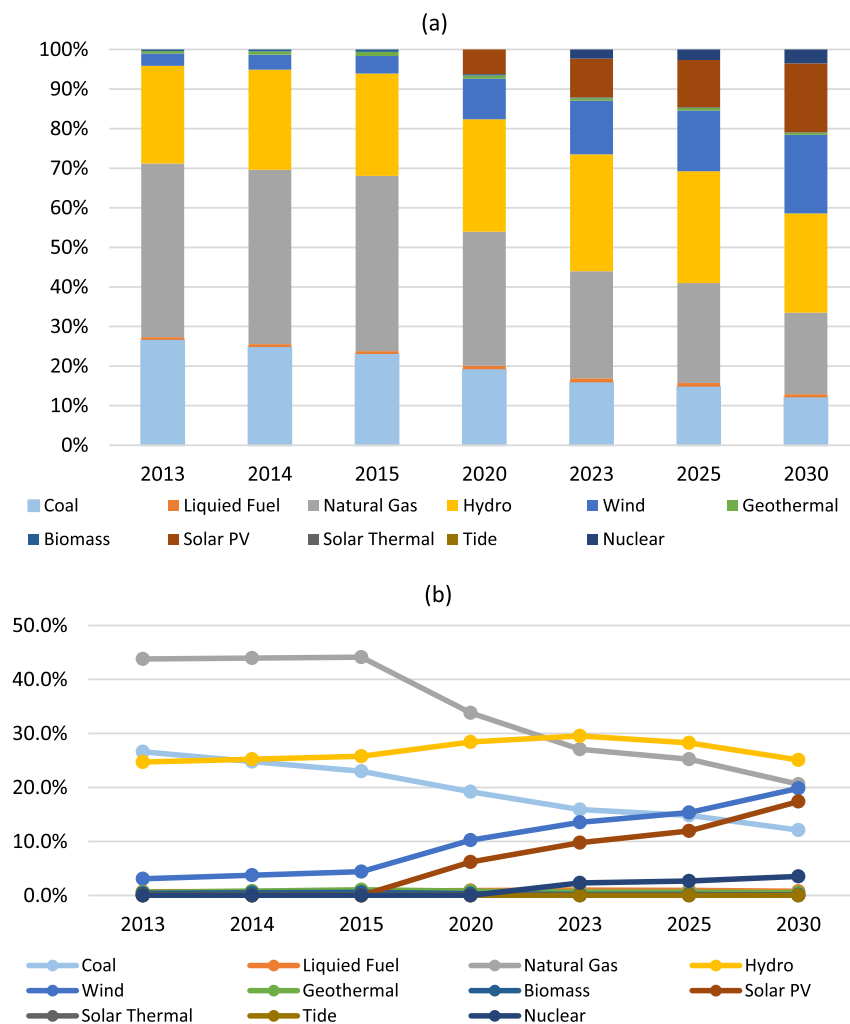

Fig. 7. Scenario 3 (Renewable Energy Focused Development Plan) Energy Mix Percentages (2013–2030) **(a)** cumulative stacked representation; **(b)** trend of percentage fluctuation Energy Mix percentages (2013–2030).

3.1. Comparison of water footprint scenario results

Expected annual water consumption and withdrawal trends are shown in Fig. 8. The results indicate that overall water withdrawal is roughly 8—10 times greater than water consumption. In Fig. 8(a), where trend based on scenario 1 is shown, total water consumption levels are expected to increase from 3.92×10^{11} gallons in 2015 to 5.04×10^{11} gallons in 2020. This value is expected to rise to 6.06×10^{11} gallons in 2025 and by 2030, we expect the total water consumption to remain relatively steady and hit to the level of 6.67×10^{11} gallons. This is mainly due to the slow and steady growth of wind and solar energy sector in the country and decline of dependencies in natural gas and hydropower. Water withdrawals, on the other hand, are expected to show a considerable rising trend because Turkish power sector relays more on coal energy and nuclear energy projects in the long run under BAU scenario resulting total annual water withdrawals of 3.18×10^{12} gallons, 3.46×10^{12} gallons, 4.09×10^{12} gallons, 5.21×10^{12} gallons in 2015, 2020, 2025 and 2030 respectively.

Fig. 8(b) represents the expected trends in water usage growth based on the scenario 2 of this study, which is, considering if the energy sector grows as per the official governmental plan. In this case, water consumption for 2020 and 2025 are comparative as compared to scenario 1, but in 2030, we expect water consumption to be 7.5% lesser than what is was in scenario 1; mainly because of less reliance water thirsty sources like coal and natural gas in the official governmental plan by 2030. Reduced dependence on coal and natural gas in scenario 2 will also result in less water withdrawals from Turkish water reserves in Scenario 2 as compared with Scenario 1. Our analysis suggests that under scenario 2, 3.5% less water will be withdrawn in 2020 while 8.3% less water will be withdrawn in 2025 and 20.15% less water will be withdrawn in 2030 as compared with BAU.

Predicted water consumption and withdrawal trends for scenario 3, renewable energy focused plan scenario, are shown in Fig. 8(c). When Turkish energy sector grows as expected in the renewable energy focused plan, we expect water consumption to be 1.2% and 1% lower than Scenario 1 and Scenario 2 respectively in 2020 and this ratio will not vary much until 2025. However, in 2030, energy mixes in scenario 3 will result in 1.3% and 9.6% more water consumption as compared to scenario 1 and scenario 2 respectively. Hence, it is revealed that energy mix having considerable contribution of renewable sources such as hydropower can result in high water consumption. Water withdrawals, however, are less in this scenario as compared to the previous two scenarios. This is because of reduced dependencies on coal, natural gas and nuclear energy. In 2020, scenario 3 withdraws 8.7% and 5.4% less water while in 2025, it withdraws 21% and 13.9% less water and in 2030, it withdraws 31.7% and 14.4% less water than scenario 1 and scenario 2, respectively.

Table 1 summarizes the expected water usages for all scenarios.

We conclude that the amount of water consumed by the energy mixture of different energy sources based on BAU are moderate as compared to the official governmental plan and renewable energy focused scenario. This is because hydropower energy consumes a great amount of water in form of evaporation from the reservoirs.

Year-wise total water consumption and withdrawals by individual scenarios are represented in Fig. 9. Fig. 10 shows the expected gallons of water usage by different energy sector in the scenarios defined. This water usage is based on the percent of the contribution made by all the sources in Turkish energy sector. Fig. 10 is the extension of Fig. 10 and it shows the results in terms of overall percentage. So, from Figs. 10(a) and 11 (a (i), (ii), (iii)), it is evident that hydropower energy sector is predicted to consume the maximum amount of water out of all the other energy sources. We can see that coal and natural gas power sectors are also expected to consume around 10%—20% of the overall water with their percentages varying over time based on their contribution in the total power generation mix. For water withdrawal comparison, Figs. 10 (b) and 11 (b (i), (ii), (iii)) show how energy sectors are predicted to withdraw water. Coal and natural gas power generation withdraw the maximum amount of water from the reservoirs for their electricity generation. Water withdrawal by nuclear power plants is expected to plunge as the power plants will come on-line and when they will start to produce electricity in coming years.

3.2. Comparison of carbon emission scenario results

Fig. 12(a) shows the comparison between the total carbon emissions under different scenarios in Turkey and Fig. 12(b) shows comparisons of carbon emissions based on the scenarios over time. If the development of Turkish energy sector continues to grow as per the Business-As-Usual (BAU) scenario, it will have highest carbon emissions as compared to Official Governmental Plan (OGP) scenario and Renewable Energy Focused Development Plan (REFDP). Under BAU scenario, carbon emissions are expected to increase at a constant pace from 1.21×10^8 tons of CO_2 equivalent in 2015 to 1.62×10^8 tons until 2025, marking an increase in carbon emissions of about 34% in just 10 years. This difference is expected to sharply increase in the following 5 years, and it is predicted that by 2025, Turkish carbon emissions under BAU scenario will go up to 2.05×10^8 tons. This enormous amount of carbon and equivalent gas emissions require about 4.8 billion tree seedling to be grown for continuously 10 years in order to curb the damages caused to the environment [74]. The primary reason in this increase in carbon emissions over time is the increased utilization of coal energy sources and steady growth of natural gas power plants.

Conversely, OGP yields relatively less carbon emissions. From 2015 to 2020, we predict an increase of about 10.7% while it will almost remain at the same level until 2025. However, we expect a sharp increase of 28% until the year 2030. To absorb the amount of carbon emitted under scenario 2, 1.12 million acers of forestland is
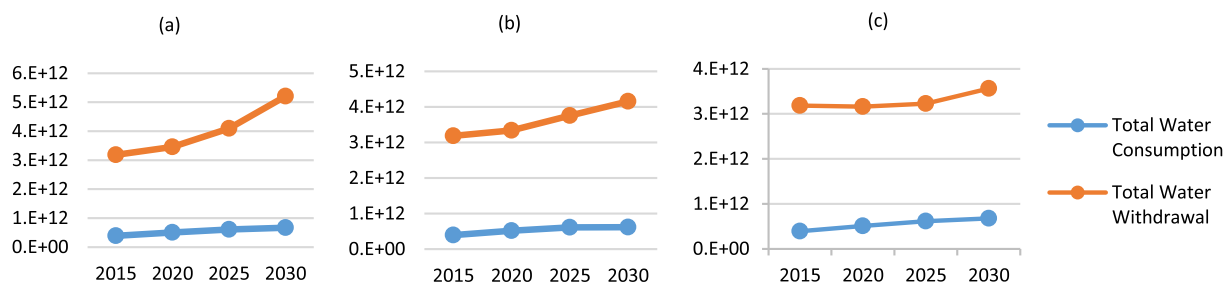

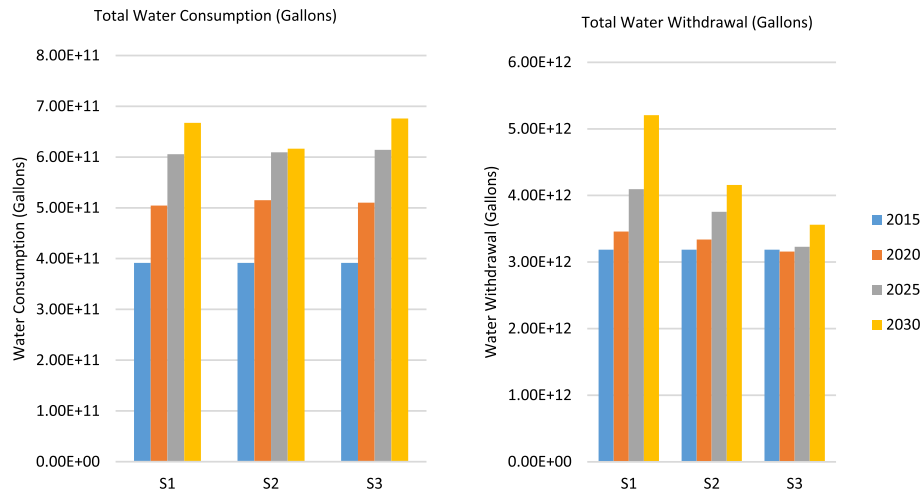**Fig. 8.** Water Usage Trend **(a)** S1, **(b)** S2, **(c)** S3 (all values are in gallons).

Fig. 9. Water usage variation **(a)** S1, **(b)** S2, **(c)** S3.
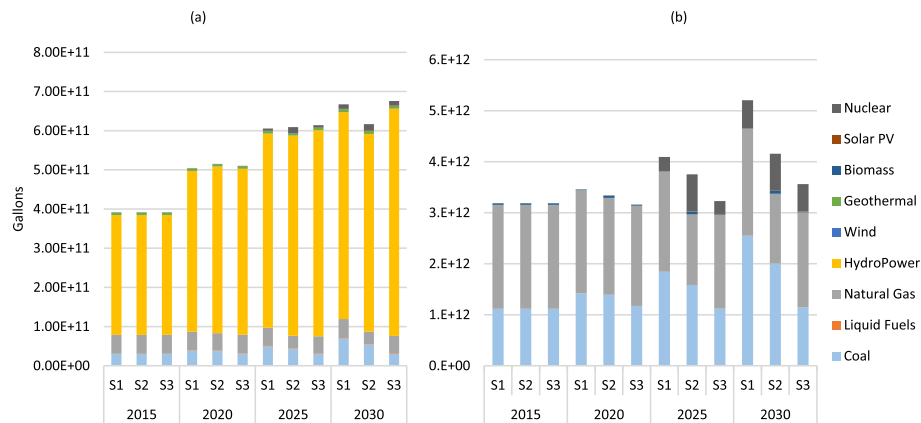

Fig. 10. Water Usage comparisons **(a)** Water Consumption, **(b)** Water Withdrawal.

required to be preserved from conversion to cropland in one year [75]. As far as REFDP is concerned, it will result in the lowest amount of carbon emissions over the period of 25 years. Carbon emissions in this scenario are expected to remain steady as of the levels of 2015.

Fig. 13 shows the contributions from all the power sources in polluting the environment and their expected trends based on different scenarios until year 2030. Coal and natural gas fired power generation sources dominate in all the scenarios while emissions from hydroelectric and solar PV power plants are to become prominent, as their contributions in overall energy sector mix will increase under REFDP scenario [76].

3.3. Water versus carbon footprints of electricity production scenarios

The scenarios and results discussed in the earlier sections shows the expected growth of Turkish energy sector and predicted average water usage in terms of water consumption and withdrawal until 2030. Predictions about overall emissions of GHGs have also been made for the same time horizon. In order to study the linkage between carbon footprint and water footprint, correlation analysis between carbon emissions versus water consumption and carbon emissions versus water withdrawal is carried out as a tool to gauge the effects of variation in carbon and water footprints.

The results presented in Fig. 14 show that under BAU scenario, total GHG emissions and total water withdrawal amounts are closely correlated — with 1:1 ratio, even more than GHG emissions and water consumption levels — with 1:0.94 ratio. Likewise, under OGP scenario, overall carbon emissions and water withdrawals have a ratio of 1:0.90, while carbon emissions and water consumption have a correlation of 1:0.76. However, REFDP scenario yields correlation values between carbon emissions versus water withdrawal and carbon emissions versus water consumption to be 1:0.63 and 1:0.53, respectively. These results give us the significance of relativeness between carbon and water footprints and their sensitiveness to the GHG emissions. For example, a correlation of 1:0.63 between GHG emissions and water withdrawal in REFDP illustrates that an increase in one factor of carbon emission will result in increase in water withdrawal, but with a factor of 0.63. Hence, based on the correlation results, REFDP is highly preferable under the threats of increased water scarcity and increasing carbon emissions.

Through this, policy makers and environmentalists will be able to see the trade-off between carbon emissions and water usage while devising the development of energy sector in Turkey. The decision support tool developed as part of this research (see appendix) is designed to enable the policy makers study the changes in water usages and carbon emissions as percentages of
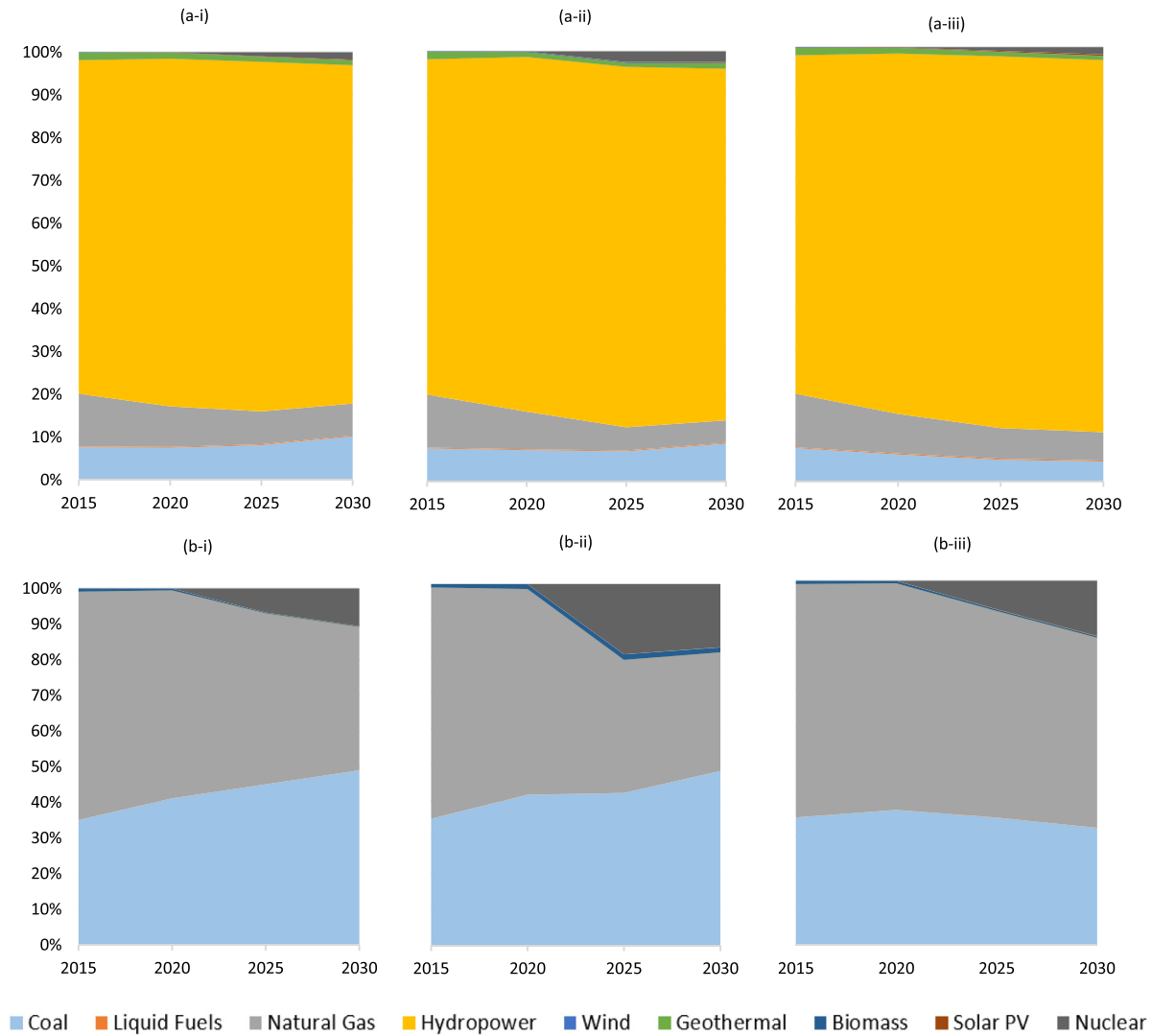
Fig. 11. Water Usage Percentage comparison **(a)** Water Consumption, **(b)** Water Withdrawal; (i) Scenario1, (ii) Scenario 2, (iii) Scenario 3.
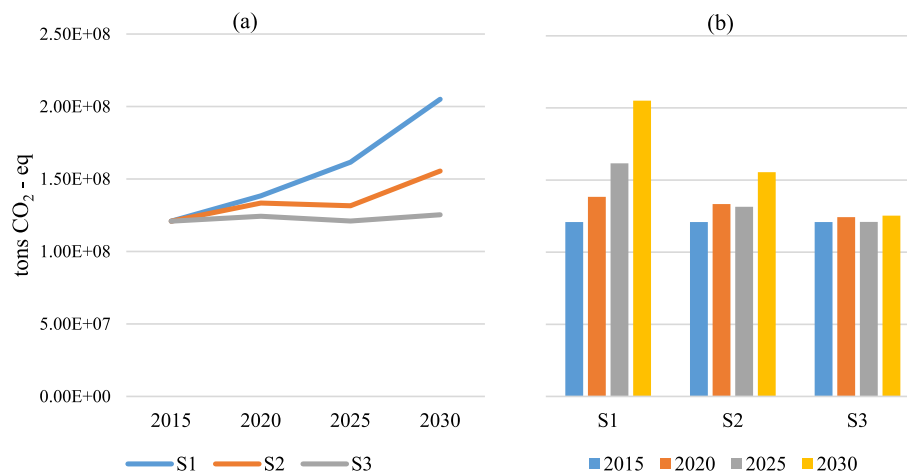
Fig. 12. Carbon and equivalent gas emissions **(a)** Yearly comparison, **(b)** Head to head comparison of scenarios.

energy mixes are changed. Therefore, the percentages can be changed and their effect on the water consumption and

withdrawals levels along with carbon emissions in the country. From our results, it is revealed that carbon and water footprints are
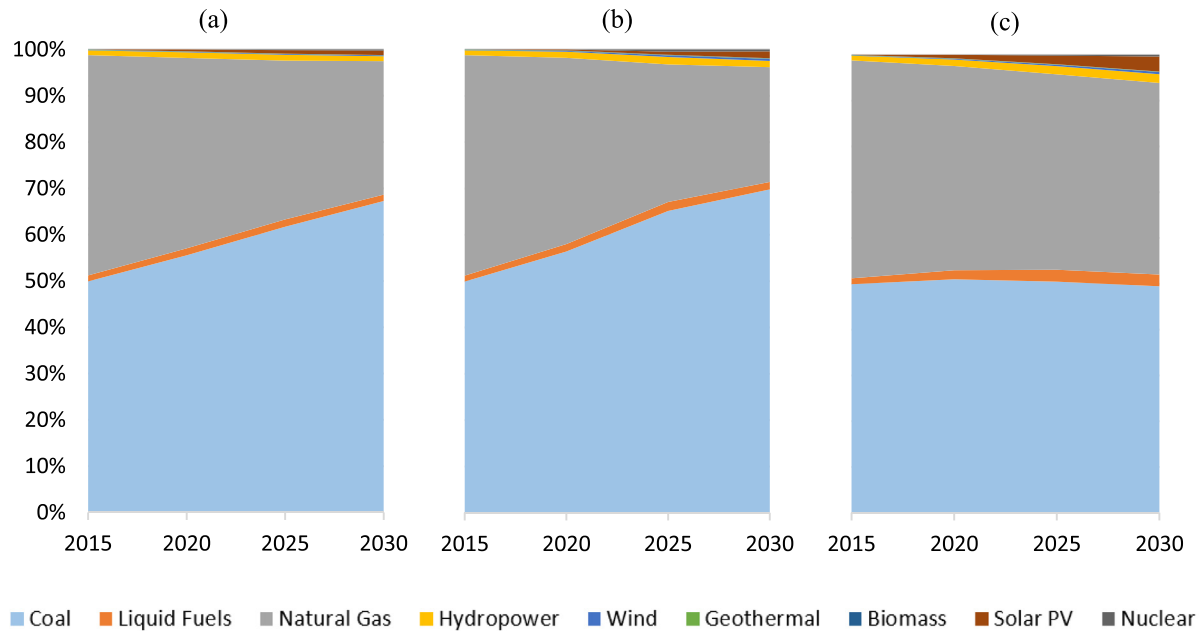
Fig. 13. Carbon Emission percentage comparison (**a**) Scenario 1, (**b**) Scenario 2, (**c**) Scenario 3.
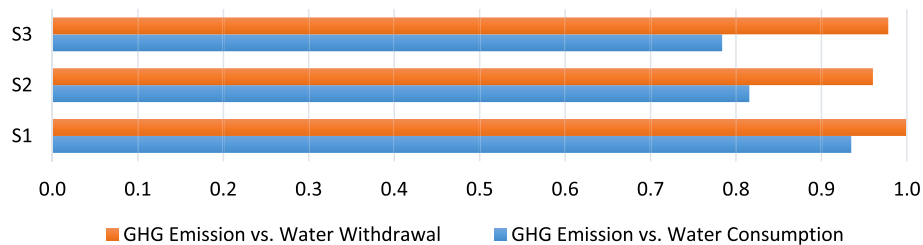

Fig. 14. Correlation analysis of GHG Emissions Vs Water Consumption and Withdrawal.

positively correlated with each other; therefore, developing policies to reduce carbon emissions with also decrease water consumption and withdrawal. Furthermore, we found that coal, natural gas, hydropower and nuclear energy consumed the great amount of water while producing electricity. Additionally coal, natural gas and nuclear withdraws much of the water as well. Similarly, coal and natural gas fired power plants contribute most to the pollution in the country. Thus, we synthesis that hydropower sources, which are taken as renewable sources of energy, are a burden on the water resources. Likewise, this study can help the policy makers in deciding the policies when planning for power plants in the country.

4. Conclusions and future work

The decision support tool developed in this study will serve in the critical decision-making about the future energy policies at national scale. Energy demand is growing at a rapid pace and various energy projects are under the phase of conceptualization and planning. Water is also becoming a scare resource and policy makers consider the implications of water parallel to the other environmental aspects while making plans of catering electricity demands. This study can be considered as a stepping-stone in developing a framework for considering the impacts of electricity production sources on national water resources in terms of water consumptions and withdrawals. The decision support tool will

enable the decision makers change their desired energy mixes and observe the corresponding results on water sources. We carried out a detailed study on the Turkish energy sector and its growth until 2030 under BAU, OGP and REFDP scenarios. Some of the general remarks and important results are summarized as follows:

- Hydropower consumes the maximum amount of water out of all the energy sources. Coal and natural gas power plants dominate in water withdrawals and carbon emissions. The findings also show that nuclear energy will also use a considerable amount of water resource, as their power plants will start to produce electricity with time.
- The Business-As-Usual (Scenario 1) consumes less water than the Official Governmental Plan (Scenario 2) and the Renewable Energy Focused Development Plan (Scenario 3) in 2020 and 2025. However, S1's water consumption will be greater than S2 and comparative to S3 by 2030. Hence, S2 is the most water efficient scenario as far as water consumption is concerned.
- Considering water withdrawals, S1 is found to withdraw the maximum water out of all the scenarios. Water withdrawal levels by individual scenarios are decreasing from S1 to S2 to S3. Therefore, S3 turn out to be the most efficient scenario in this case.
- S3 is the suggested scenario for future energy policy development because it is found to use the least water and emit the least carbon emissions among other scenarios.

- Water usage and GHG emissions are strongly correlated in S1. In S2, correlation weakens to about 12% and to 25% in S3 as compared with S1. Hence, re-establishing the eco-friendliness of REFDP scenarios in comparison with others.

The energy-water nexus is a tradeoff between water consumptions and water withdrawals by the individual energy sources [79]. Water usage is varied significantly from one power plant to another and it is dependent on many factors one of which is the cooling technology used. In this study, the average multipliers are used. However, maximum and minimum ranges of the results can be seen in the supporting information file mentioned in the appendix. Our aim for the future study is to categorize the power plants in Turkey through building a database and linking the decision support tool with it. In addition, we would like to extend this study to the other countries such as UK, European Union and United States.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2017.07.124.

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