A Systematic Analysis of Bioenergy Potentials for Fuels and Electricity in Turkey: A Bottom-Up Modeling

Danial Esmaeili Aliabadi, Daniela Thrän, Alberto Bezama and Bihter Avşar

1. Introduction

1.1. Global Warming: A Thread Ahead

For decades, scientists have been warning about the negative consequences of climate change on society. In late 2015, as the public demand from authorities grew, a considerable majority of countries decided to boost their actions to restrict a global-mean temperature rise to 1.5 °C above pre-industrial levels. This ambitious target in the Paris Agreement was designed to be achieved through countries' contributions (i.e., nationally determined contributions). Unlike the Kyoto Protocol, which expired in 2012, the Paris Agreement differentiates countries' responsibilities by distinguishing "developed" countries from "developing" countries. Although this approach enables developing countries to improve their future contributions, relying on self-imposed contributions may result in countries declining to make ambitious targets (Pauw et al. 2019). That is why some countries have requested to be recognized as a member of non-Annex I countries (UNFCCC 2018), while others find targets not bold enough. For instance, the European Union (EU) has further propelled the actions of members in the "Green Deal" by committing to slash emissions by half from 1990 levels, by 2030 (European Commission 2019). The United States also rejoined the Paris climate agreement after leaving it for a short interval in the previous administration (Pedaliu 2020).

Many solutions have been proposed to slow down, and eventually stop, global warming, among which are decarbonizing societies using renewable resources and demand response management. Moving toward a bio-based economy is one of the proposed solutions that promise a cleaner production of energy for various sectors such as industries and transportation. This is particularly important since most efforts in the past were solely focused on the power sector. As stated by experts and policymakers around the world, the underlined targets in the Paris Agreement are difficult to reach if we rely on renewable electricity alone (FSR 2019). This stems from the fact that emissions from energy-intensive industries (such as iron and steel, and cement), as well as the transport sector, comprise a considerable share of the total greenhouse gas (GHG) emissions every year. These hard-to-abate sectors require storable energy sources with high energy density (Friedmann et al. 2019). For overcoming this challenge, currently, there are several technological concepts under development (e.g., all-electric commercial jets).

1.2. Gas-Power Network

According to the World Energy Outlook, which is published by the International Energy Agency (IEA), natural gas is expected to play a significant role in the global energy landscape in the future by replacing coal (IEA 2020b). Using gas-fired peaker power plants, natural gas can also hedge against the intermittency of renewable sources such as solar and wind (United Nations 2020). In fact, the EU believes that any cost-optimal solutions to achieve a near-zero carbon energy system by the mid-century should consider a "dual" gas-power network (Bowden 2019). Yet, combusting fossil natural gas is destructive for the environment, even though it pollutes less than coal and crude oil; therefore, in long-term solutions, natural gas should be replaced with other renewable alternatives.

Methane (CH_4) production from biological origins (bio-CH_4) and (green) hydrogen (H_2) can be suitable substitutes for natural gas. Due to their similar compositions, bio-CH_4 is easier to implement than H_2, since it does not require huge investments in infrastructures. Indeed, existing natural gas facilities for storage and transportation can also be used for bio-CH_4 (Matschoss et al. 2020). Thus, through investment grants and tax incentives, many countries invest heavily in the decarbonization of the gas sector using bio-CH_4 (Brémond et al. 2020). While bio-CH_4 can partially fulfill the energy demand, we should also prevent fugitive CH_4 emissions in various sectors, as the detrimental impact of CH_4 on the climate is much higher than carbon dioxide (CO_2). As a matter of fact, the sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) emphasizes that methane emissions are responsible for 0.5 °C of warming to date (IPCC 2021, Figure SPM.2).

1.3. Turkey's Current Status

Turkey is a developing country and a member of the Organization for Economic Co-operation and Development (OECD), which is growing to be an influential player in West Asia and southeastern Europe. Current Turkey's energy consumption per capita falls short when compared with other OECD peer countries, although this is expected to change (Difiglio et al. 2020). Turkey is investing heavily in the energy sector to support its rapidly growing economy. Unfortunately, Turkey's domestic reserves are not adequate to fulfill its demands; thus, the nation has to rely on oil and natural gas imports from neighboring countries such as Russia, Iraq, Azerbaijan, and Iran (Esmaeili Aliabadi 2020). Owing to imported fossil fuels, Turkey's energy trade deficit is soaring to a massive amount, with natural gas being the second important cause after crude oil and petroleum products (Erkoyun et al. 2020).

In order to ameliorate the trade deficit and achieve supply security, Turkey is diversifying its energy generation portfolio by investing in domestic renewable resources under law No. 6094, including bioenergy. The Turkish government introduced technology-specific feed-in tariffs (FITs), the so-called renewable energy resources support mechanism (YEKDEM, by its Turkish acronym). According to YEKDEM, the government is obligated to purchase the generated power for a decade with fixed prices from the renewable facilities that are commissioned prior to July 2021 (EMRA 2005; IEA 2021). As appeared in Table 1, this support mechanism also provides incentives to local energy technologies.

Table 1. Technology-specific feed-in tariffs according to the renewable energy resources support mechanism (YEKDEM).

Technology	Base Incentive (US ¢/kWh)	Local Equipment (US ¢/kWh)	Total (US ¢/kWh)
Concentrated solar power	13.3	9.2	22.5
Solar photovoltaics	13.3	6.7	20
Biomass and waste	13.3	5.6	18.9
Geothermal	10.5	2.7	13.2
Wind	7.3	3.7	11
Hydro	7.3	2.3	9.6

Source: Table by authors, data from EMRA Law No. 5346 (EMRA 2005).

The YEKDEM scheme caused a boom in the deployment of clean energy technologies such as wind and solar; however, as depicted in Figure 1, bioenergy did not receive the same attention (Esmaeili Aliabadi 2019). As of January 2021, the total installed capacities of solar power plants are more than six times of biogas, biomass, and waste heat power plants combined.

Despite the low utilization of biogas as a fuel source for electric power production, which is not on par with other renewable resources, Turkey's biogas production potential is estimated to be over 221 PJ per year in 2016 (Daniel-Gromke et al. 2016). The biogas production efficiency is a function of both biological matter properties (e.g., lignocellulose content) and the production parameters (e.g., technology). In Turkey, firewood, as the classic biomass fuel, attracts more attention for energy production, as it is convenient to process and have a high production rate; however, other biomass sources such as agricultural residues including hazelnut shell, tea waste, and wheat straw have been utilized to meet the energy demand. Maltsoglou et al. (2016) provide regional assessments for the availability and potential of agricultural residues for heat and power production in Turkey. Preparing an up-to-date regional plan for bioenergy is vital since there is no silver bullet that can solve the energy issue in every province.

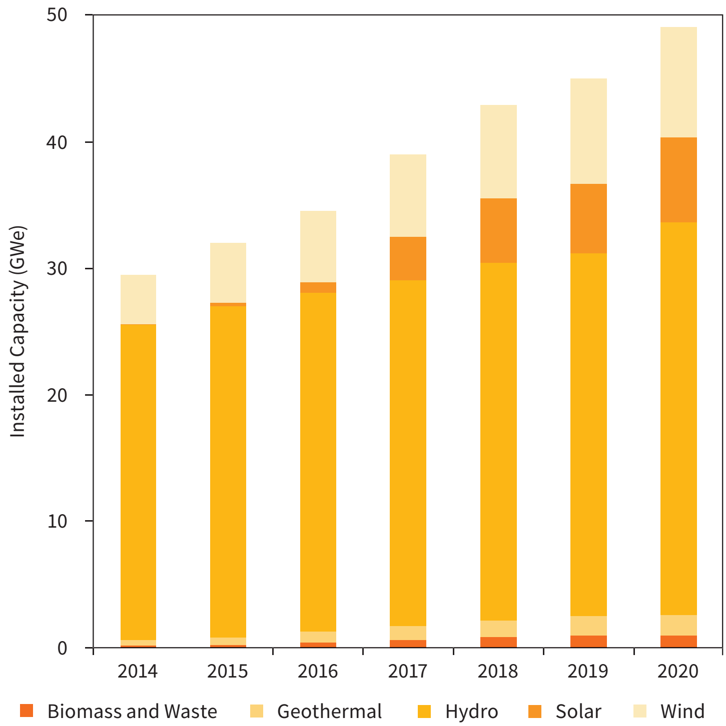

Figure 1. Breakdown of installed capacity by renewable technologies from 2014 to 2020. Source: Graphic by authors.

In the transport sector, biodiesel and bioethanol production is again supported by law. From 2018, Turkey's energy market regulatory authority made it compulsory to blend a minimum of 0.5% biodiesel in diesel oil (Tiryakioglu 2017). In 2014, Turkey increased the percentage of bioethanol blended with gasoline to 3% from the initial value of 2% in 2013. Thus far, bioethanol is produced in Turkey almost entirely from sugar beet, corn, and barley (AGWeek 2011; Ozdingis and Kocar 2018). Producing bioethanol fuel from limited energy crops can be disrupted frequently in the long term, as it competes with the food and medical supply chains. For example, due to the high demand for disinfectants amid the pandemic, bioethanol production for gasoline was suspended in 2020 (Erkul 2020).

Supporting biofuels is not limited to Turkey. In Germany, similar policies are in place since 2015 through a GHG-based quota, which requests fuel suppliers to mix biofuels with conventional fuels such that the resulting mixture achieves a specific (i.e., 6% in 2020) GHG mitigation (Meisel et al. 2020).

While Turkey is facing unique challenges, it shares a common ground with other developing countries; hence, successful practices can be adopted by the rest of the world. To this end, we calculated Turkey's sectoral GHG emissions until 2040, using a bottom-up technology-oriented energy model. Analyzing the collected information, we propose strategies to curtail GHG emissions by promoting bioenergy production and consumption.

2. Materials and Methods

2.1. Energy Systems Modeling

In order to model intertwined energy systems, there are two fundamental modeling perspectives: the top-down macroeconomic approach and the bottom-up engineering approach. Both of these approaches have their own advantages and disadvantages: for instance, top-down models assume an unalterable world, whereas bottom-up models account for technological breakthroughs over time. Bottom-up models serve as the practical method to estimate energy trends in mid- and long term (Esmaeili Aliabadi et al. 2021).

In order to evaluate the total GHG emissions at the country level, the whole energy system should be considered, with all components and their interactions. To this end, a bottom-up technology-rich optimization model based on TIMES[1] (Loulou et al. 2005) has been developed, in which parallel technologies compete to satisfy end-use demand with minimum costs and within the frame of financial, environmental, and technological constraints. As illustrated in Figure 2, the developed model creates a complex network of processes, in which commodities are being acquired (imported or extracted), transformed (through conversion processes),

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1 TIMES is the acronym for The Integrated MARKAL-EFOM (MARKet ALlocation-Energy Flow Optimization Model) System. The TIMES source code can be acquired from https://github.com/etsap-TIMES/TIMES_model (accessed on 21 September 2021).

and transferred to be used by others. The results determine the optimal technology mix for each demand service until 2040, using 1200 processes, 181 commodities, and over 50 thousand data values.

In the proposed model, years are divided into eight time slices distinguishing day and night in each season. Hourly available datasets, such as electricity demand, wind speed, precipitation, and solar irradiation in each region, are transformed to be in accordance with the specified setting.

While the developed model consists of a single region (i.e., Turkey), it respects the regional characteristics of its elements. For instance, the availability factor of wind farms considers the local wind speed and employed technologies.

Considering the technical properties, we assigned emission factors (EFs) to processes for various gases (CO_2, CH_4, and N_2O). To assess the potency of GHGs in trapping heat, experts employ a relative measure called global warming potential, by which the greenhouse effects of GHGs are compared with those of CO_2 as the reference gas. We used coefficients mentioned in Gillenwater et al. (2002, Table 2) to calculate the total annual CO_2-equivalent emissions.

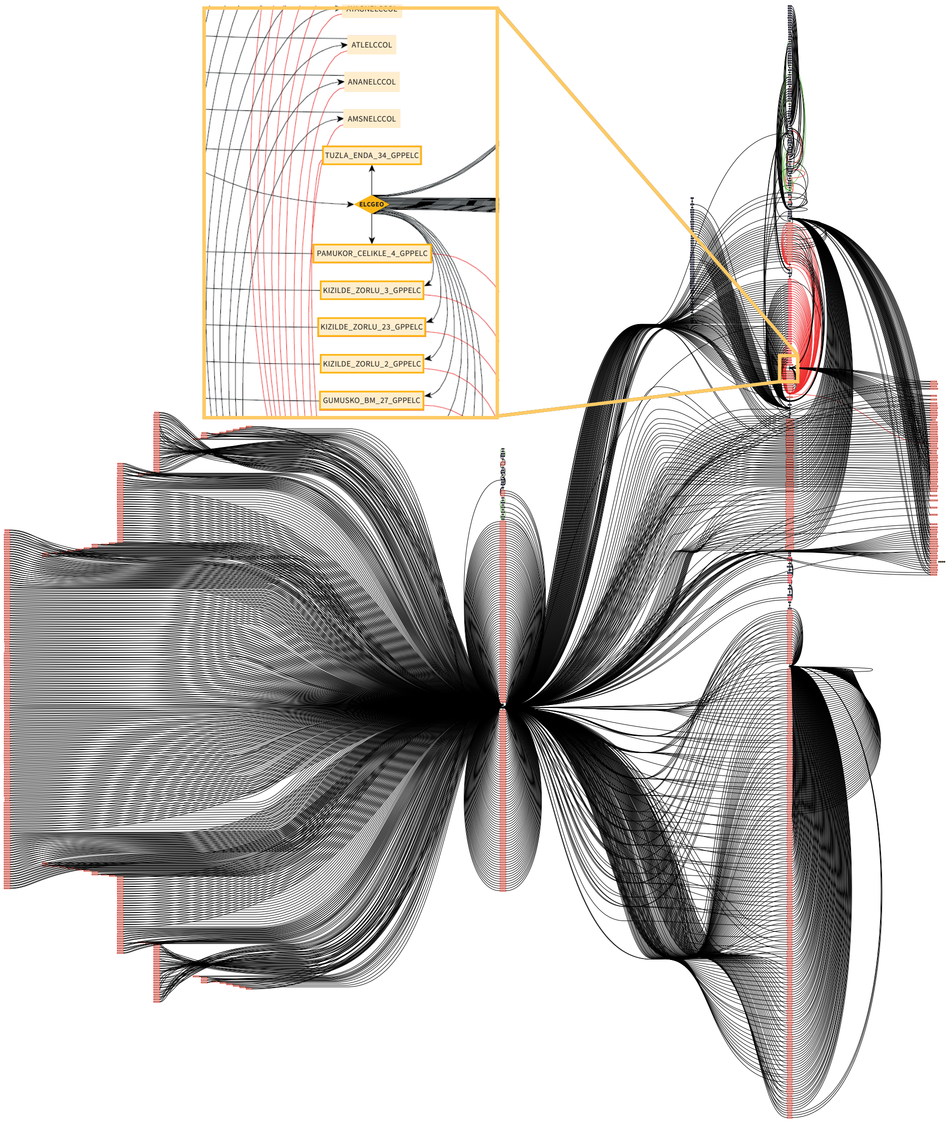

Figure 2. Magnifying a section of the reference energy system. In the magnified section of the network, one can see the exploitable geothermal energy is redirected to individual geothermal power plants, which illustrates the level of details in processes. Interested readers are invited to zoom into the digital version of this figure for the details. Source: Graphic by authors.

2.2. Scenarios

For this study, we devised two scenarios: (1) the current policy (CP) scenario, in which established regulations and available technologies were taken into account, and (2) the pro-bioenergy (Pro-Bio) scenario, in which bioenergy was used intensely for producing liquid fuels and electricity.

In the pro-bioenergy scenario, we assumed that YEKDEM (or the replacing mechanism) continues supporting bioenergy (IEA 2021) and that an aggressive approach is adopted to produce biofuels in the transport sector. We adopted technology descriptions of the BioENergy OPTimization (BENOPT) model (Millinger 2020; Millinger et al. 2021) for technologies that convert crops and biomass residues to liquid biofuels, heat, and electricity. Specifically speaking, under the Pro-Bio scenario, methane emissions from dairy and non-dairy cattle and fugitive emissions from natural gas reserves were redirected to power and heat sectors. Furthermore, waste cooking oil was purchased and transformed into biodiesel using two technologies:

- Hydro treating vegetable or waste cooking oil;
- Producing fatty-acid methyl ester via transesterification of cooking oil.

Due to an active tourist sector in Turkey, centralized management of waste oil is possible to a great extent via unions[2]. Turkey's government can further support this policy using tax incentives. Nonetheless, producing biodiesel from waste cooking oil is limited to consumption in the country. To relax this constraint, oil (i.e., lipid) production from microalgae is assumed to become economically viable in the future.

To achieve commercial-scale production of algae-based biodiesel, scientists and engineers should overcome many techno-economic challenges such as enhancing lipid production and designing an efficient dewatering method. In order to enhance lipid production, biologists are genetically engineering microalgal strains using state-of-the-art technologies such as CRISPR-cas9, which can decrease the cost of biodiesel downstream (Lü et al. 2011; Ng et al. 2017; Radakovits et al. 2010). Furthermore, open pond systems for microalgae cultivation are prone to parasites and invasive species; therefore, scientists need to investigate gene editing strategies to increase microalgae strain's tolerance against a/biotic stressors. The current problem with oil production from microalgae is dewatering, which is energy intensive.

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[2] In Turkey, the alternative energy and biodiesel manufacturers union (ALBIYOBIR by its Turkish acronym) is a major association that collects waste cooking oil for biodiesel production.

Researchers are investigating energy efficient dewatering methods that can be combined with the lipid extraction step (Ghasemi Naghdi et al. 2016).

By enhancing the technology and increasing yield, we can make microalgae an attractive alternative to produce oil on a commercial scale. Under the Pro-Bio scenario, we assumed a higher cost for producing energy from microalgae than waste cooking oil that drops rapidly over time due to the learning effect. All in all, we introduced five new technologies that produce heat and electricity from biogas, biomethane, and vegetable oil. Furthermore, we added four new technologies to produce bioethanol and biodiesel from lignocellulose, sugar beet, microalgae, and waste cooking oil.

Finally, no upper bound was set for the GHG emissions under the Pro-Bio and CP scenarios. Table 2 summarizes the differences between the two scenarios.

Table 2. Differentiating components under each scenario.

Component	Type	Current Policy Scenario	Pro-Bio Scenario
Fugitive gases	Technology	Release into atmosphere	Utilized for heat production
Technologies	Technology	Available technologies	Adopted from BENOPT
YEKDEM	Policy	Ends at 2021	Continues until 2040
Blending bioethanol with gasoline	Policy	increasing the blending ratio to about 8% by 2040	increasing the blending ratio to about 20% by 2040
Blending biodiesel with diesel	Policy	increasing the blending ratio to 0.7% by 2040	increasing the blending ratio to 20% by 2040

Source: Table by authors.

It is noteworthy to mention that the results of the presented model in this manuscript should not be compared with Difiglio et al. (2020), as the presented model was modified thoroughly to include only publicly available information and datasets.

3. Results

3.1. Current Policy Scenario

The total GHG emissions (CO_2-equivalent) from each sector under the CP scenario are illustrated in Figure 3a. Due to the massive deployment of solar photovoltaics and wind turbines, the GHG emission intensity of the power sector is expected to decrease from ∼490 g CO_2-eq./kWh, in 2020, to 252 g CO_2-eq./kWh, in 2040. This declining trend results in dropping GHG emissions from the electric power sector despite higher electricity demand.

As one can see from Figure 3b, the total GHG emissions of Turkey (including non-energy sectors such as agriculture and chemical industries) are steadily rising. The color bars in Figure 3b are adopted from the Climate Action Tracker website[3]. The colors represent different ranges in the selected years. The emission abatement strategies within these ranges are likely to cause global warming mentioned in two ends of that particular color if all countries follow similar approaches.

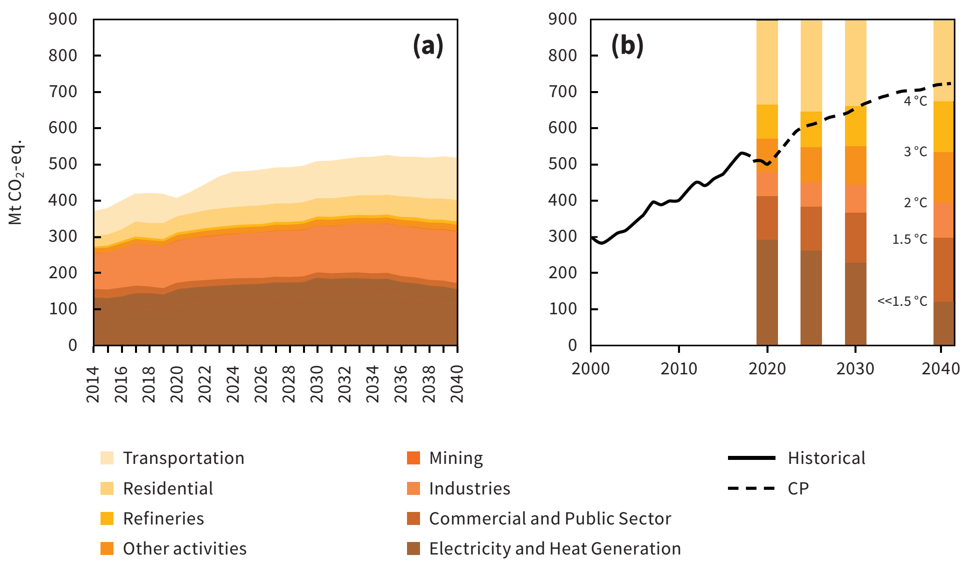

Figure 3. (**a**) Sectoral GHG emissions (expressed in Mt CO_2-eq.) from 2014 until 2040; (**b**) comparing the total GHG emissions with the Paris climate agreement. The solid line shows the historical emissions, and the dashed line displays the projected emissions. Source: Graphic by authors.

According to our calculations, the existing GHG abatement strategies in Turkey are highly insufficient. Although the current trend is above an acceptable level, it is below Turkey's intended nationally determined contribution, which was 929 Mt CO_2-eq. in 2030 (Republic of Turkey 2015).

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[3] Please see https://climateactiontracker.org/countries/turkey/ (accessed on 20 September 2021).

Further investigation in Figure 4a shows that methane, which can be used as a fuel source, comprises a considerable amount of emissions. By exploiting emitted CH_4, we can prevent polluting the atmosphere with a gas multiple times stronger than CO_2 in trapping heat, and simultaneously, combust less of imported (and relatively expensive) natural gas. Among various CH_4 emission sources in Figure 4b, the agriculture and mining sectors contribute between 69% and 91% of the total CH_4 emissions from 2014 to 2040. It is estimated that Turkey holds 679 billion cubic meters of shale gas reserves in the Thrace region and southeastern Anatolia[4]. Extracting these resources as planned, with similar EFs as the current technology, can emit a considerable amount of CH_4 into the atmosphere. Among other sources of bio-CH_4 emissions in the agriculture sector, dairy and non-dairy cattle can be counted as big-ticket items.

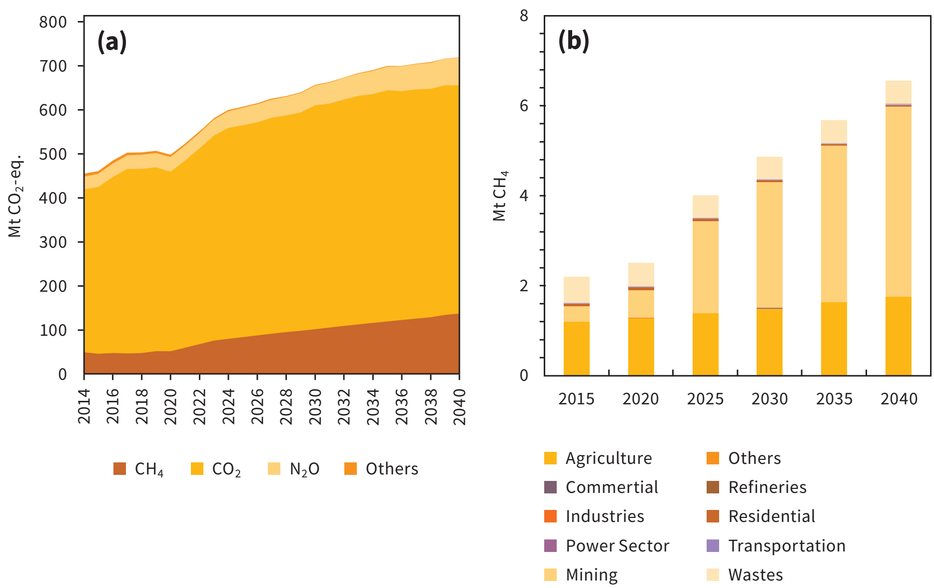

Figure 4. (**a**) Total GHG emissions by type (expressed in Mt CO_2-eq.) from 2014 until 2040; (**b**) methane emissions from various sectors. Source: Graphic by authors.

[4] Please see https://politicstoday.org/what-is-turkeys-shale-gas-potential/ (accessed on 20 September 2021).

In the transportation sector, vehicle ownership growth leads to higher fuel consumption. Subsequently, there are intentions to increase the blending ratio of bioethanol and biodiesel. Increasing the blending ratio of bioethanol to about 8% and biodiesel to 0.7% by 2040 can double these biofuels consumptions (15.7 PJ)[5]. To increase the blending ratios, while not competing with food crops, it is required to adopt better production technologies such as second-generation bioethanol.

In rural areas, biomass is still being exploited for residential space heating, water heating, and cooking. However, we expect biomass consumption to decline, driven by electrification and gasification in the residential sector.

3.2. Pro-Bio Scenario

According to our calculations in Figure 5a, the total GHG emissions of Turkey can reach 570 Mt in 2040. Under the Pro-Bio scenario, Turkey can produce approximately 250 PJ biodiesel and bioethanol per annum by 2040, using waste cooking oil, microalgae, lignocellulosic biomass, and food crops (see Figure 5c).

In the power sector, the installed capacity of biomass-based power plants can raise to 11 GW by 2040, of which combined heat and power using waste cooking oil would play a significant role (see Figure 5b). Subsequently, the GHG emission intensity in the power sector would drop to 226 g CO_2-eq./kWh in 2040.

Finally, as illustrated in Figure 5d, the biomass consumption in the building sector in 2040 is negligible (∼48 PJ), which paves the way for better management of forests. As reported by the IEA (2020a) and Schimschar et al. (2016), biomass consumption share in buildings for space heating is decreasing, owing to better standards, and electrification and gasification of the residential sector, especially in rural areas.

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[5] Producing biodiesel over 0.7% ratio is difficult to achieve when waste cooking oil is solely considered.

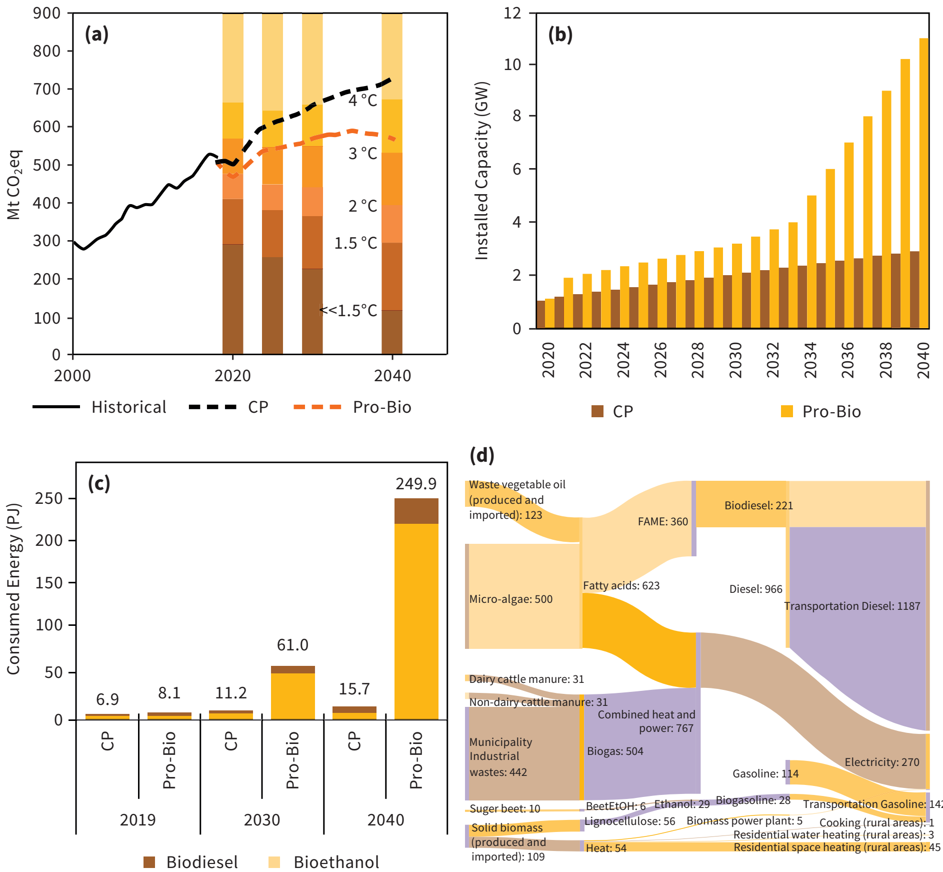

Figure 5. (**a**) The total GHG emissions under the CP and Pro-Bio scenarios; (**b**) the total installed capacity of power plants based on biogas, biomethane, biomass, and waste oil; (**c**) bioethanol and biodiesel consumption in the transportation sector; (**d**) the energy flow from biomass, wastes, and biofuels (PJ) in Turkey's energy system under the Pro-Bio scenario in 2040. Source: Graphic by authors.

4. Discussion

In this chapter, we assessed the effect of introducing biogas and biofuels more actively in Turkey's energy system till 2040. In the CP scenario, the contribution of biofuels to the transport sector is 275.4 PJ from 2014 till 2040, which displaces about 7.3 Mt of diesel and gasoline and avoids emitting 20.64 Mt CO_2-eq. into the atmosphere. However, by assuming higher biofuel blending ratios in the Pro-Bio scenario, an extra 153 Mt CO_2-eq. GHG emissions can be avoided within the same time frame. This is equivalent to not purchasing 57 Mt of petroleum products, which, by itself, can improve Turkey's trade deficit.

To provide the additional biofuels, a wider range of technical options should be considered. For this reason, preparing a strategic plan to develop bioenergy in each region respecting their ecological characteristics (ecotype) is crucial. In short-term solutions, agricultural residues produced on a provincial scale can play a significant role, as they entail fairly low costs and great accessibility. For instance, Turkey is one of the major hazelnut producers, and hazelnut is the most important tree nut crop for the country's economy; hence, the Turkish hazelnut cultivar's genome has recently been sequenced to unravel the critical properties for crop improvement (Avşar and Esmaeili Aliabadi 2017; Lucas et al. 2021). Most hazelnut production in Turkey occurs in Ordu, Samsun, and Giresun near the Black Sea Coast. The centralized production of hazelnut in these neighboring provinces provides a unique opportunity to exploit hazelnut wastes and shells as the main agricultural wastes for biogas production (Şenol 2019). Simultaneously, endemic terrestrial plants, such as Origanum Sp. Tekin-2017 (Cilgin 2020), should be evaluated to analyze their applications in biodiesel production.

Utilizing aquatic plant-like organisms, such as microalgae, can also be seen as a viable alternative to produce oil for biodiesel production. According to our calculations, the total surface area of all reservoirs behind hydroelectric power plants is above 4451 km^2. When the lakes are included, the total surface area of these waterbodies surpasses 8000 km^2. This potential can be utilized to cultivate microalgae for fuel production. Assuming a 45 tFM yield per hectare and year, Turkey can produce over 83.53 PJ of energy by exploiting 50% of this potential. Hence, achieving 500 PJ in 2040, which is required by the Pro-Bio scenario, might be infeasible without considering coastlines (e.g., the Black Sea and the Mediterranean Sea). To this end, investing in offshore technologies similar to the Offshore Membrane Enclosures for Growing Algae (OMEGA) project (Colen 2014; Wiley 2013) seems inevitable, which requires solving many techno-economic challenges to tap into this potential.

As the market diffusion of intermittent renewable resources (e.g., solar and wind) increases, and coal-burning power plants become less attractive for investors, independent system operators will have to be prepared to cope with the power balancing issue in real time. Flexible biogas-burning power plants can be viewed as a green alternative to gas-fired peaker plants to produce power on demand. Managing biogas optimally can complement the advantages of other renewable resources (Dotzauer et al. 2019; Lauer and Thrän 2018). Considering the technology mix, the produced power in the Pro-Bio scenario from biogas and vegetable cooking oil can prevent emitting 241.53 Mt CO_2-eq. until 2040.

5. Conclusions

In this chapter, a TIMES-based model was employed to compare the impact of higher bioenergy consumption in Turkey on greenhouse gas emissions via contrasting scenarios: the current policy and pro-bioenergy. According to the results, Turkey needs to invest in novel technologies to resolve the competition between biofuels and other critical supply chains (e.g., for food and medical applications), as the currently used waste cooking oil and sugar beet are hardly enough to support notable consumption levels. Furthermore, flexible biogas-based power plants should be supported using FITs as a green alternative to gas-fired peaker plants to hedge against volatilities caused by intermittent renewable sources. By so doing, power systems will be enabled to invest more in harnessing energy from solar and wind.

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Abbreviations

The following abbreviations are used in this manuscript:

ALBIYOBIR	The alternative energy and biodiesel manufacturers union
BENOPT	BioENergy OPTimization model
CAS9	CRISPR-Associated Protein 9
CRISPER	Clustered Regularly Interspaced Short Palindromic Repeats
CP	Current Policy scenario
EF	Emission Factor
EFOM	The Energy Flow Optimization Model
EU	The European Union
FIT	Feed-in tariff

GHG	Greenhouse gas
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
km	Kilometer
kWh	Kilowatt hour
MARKAL	Market allocation
Mt	Million tonne
OECD	Organization for Economic Co-operation and Development
OMEGA	Offshore membrane enclosures for growing algae
PJ	Petajoule
Pro-Bio	Pro-Bioenergy scenario
tFM	Tonne of Fresh Matter
TIMES	The Integrated MARKAL-EFOM System
US	The United States of America

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