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The Effect of Technological Development on Renewable Energy

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ABSTRACT

Renewable energies have an essential role in the reduction of external dependency of countries by meeting their energy needs from domestic resources, sustainable energy use as a result of diversification of resources and minimizing the damage to the environment from energy consumption. The study aims to measure technological developments' impact on Turkey's renewable energy production. Therefore, this study uses annual time series data on Turkey from 1980-2022 to investigate the causal link between technology and renewable energy production. This study applies Augmented Dickey-Fuller (ADF) (1981), Phillips-Perron (PP) (1988), Kwiatkowski-Phillips-Schmidt-Shin (KPSS) (1992) and Ng-Perron (2001) tests for data analysis. In the long run, it has been found that there is a significant positive relationship between technological development and renewable energy; in addition, it has been found that there is a bidirectional causality relationship between renewable energy production and economic growth in the short term.

KEYWORDS

Energy, Renewable Energy, Technology, Progress, Economy, Growth, Development, Turkey

INTRODUCTION

Energy is essential for uninterrupted economic development, driving industry, agriculture, and other vital activities. The goal of the energy sector is to maintain the sustainability of the developing economy while meeting the growing population's energy needs at the lowest possible cost and within a secure supply system (Özdemir, 2019). Renewable sources—such as solar, wind, hydro, biomass, geothermal, and others—and non-renewable sources— like oil, coal, and natural gas—respond to this need.

There are various renewable and non-renewable (conventional energy sources) energy sources worldwide. Most renewable energy sources derive from the sun. Fossil fuels (non-renewable or conventional energy sources), a dominant energy source globally, faced a turning point in 1973 during the oil-crisis when rising oil prices prompted a shift in energy strategies (Cohen, 2021). Following the crisis, many countries recognized the growing awareness surrounding renewable energy opportunities. Thus, they began searching for alternative sources to meet and sustain increasing and

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diverse energy needs. This search continues today, prompting studies on renewable energy resources (Karagol & Kavaz, 2017)

The legal definition of the International Renewable Energy Agency (IRENA) was ratified by 108 member states and the European Union (EU) in February 2013. It states that "Renewable energy includes all energy sustainably produced from renewable sources, including bioenergy, geothermal, hydropower, ocean, solar, and wind" (IRENA, 2013). According to the International Energy Agency (IEA), renewable energy resources are derived from natural processes and reproduce at higher rates than they are consumed. The agency identifies the following renewable resources for electric and heat: solar, wind, ocean, hydropower, biomass, geothermal resources, biofuels, and hydrogen (IEA, 2002).

Renewable energies differ from fossil fuels because they are clean, inexhaustible, and increasingly competitive. They produce neither greenhouse gases (GHGs), which impact climate change, nor polluting emissions. Unlike fossil fuels, renewable costs are falling at a sustainable rate.

The literature reveals many studies on renewable energy resources. The current study provides an overview of renewable energy resources, highlights recent developments in the field, and examines how technological innovations impact these resources. It also offers a detailed analysis of how the use of renewables impact economic growth. The study's results are significant for countries investing in renewable energies and purposefully developing a future perspective.

Concerning the contribution of literature, the study gives insight into the channels through which technological innovations impact renewable energy production. In contrast with prior studies that opted for renewable energy consumption as their primary dependency variable, this study uses renewable energy production as its primary dependent variable. Furthermore, studies that focus on country-specific factors, such as government policies and regulations influencing renewable energy production, can complement this research.

RENEWABLE ENERGY RESOURCES

Energy has been a fundamental need for maintaining the economy—encompassing industry, agriculture, and other vital activities—from the past to the present. Rapid economic and technological developments have increased energy demand. Most power needs are met through conventional energy resources like crude oil, coal, and natural gas. Economic, political, and environmental concerns are at stake in countries dependent on fossil fuels when assessing the future of global energy markets (Qin et al., 2012).

In assessing future energy demands, British Petroleum (2012) forecasts that the need to generate power will double due to high population growth rates, industrialization, and developments in transportation (Utama et al., 2014). Hence, fossil fuel sources will be depleted. According to the Peak Oil theory, crude oil production has reached its highest level and will progressively decline until it eventually ceases (Bardi, 2009; Bilgili et al., 2017). As detailed in Li (2017), the world's oil production was expected to peak in 2010 before falling by 30% in 2050. In parallel with oil, the world's natural gas production should rise by 2025 and remain unchanged through 2045. By 2050, global natural gas production is projected to be 20% lower than its peak, while the world's coal reserves are expected to increase until 2030, after which they will begin to decline. Compared with 2004, the overall use of fossil fuels will be 20% lower by 2050 (Lee & Jung, 2018). To that end, sustaining energy demands is essential (Ahmad & Tahar, 2014).

Vivoda (2012) stated that energy security is the availability of various types of energy at reasonable prices and in adequate quantities without leaving unchangeable impacts on the environment and the economy. The key to maintaining economic processes is energy safety, providing an uninterrupted power supply (Kruyt et al., 2009).

Most studies consider energy prices a vital component of the energy security equation. Volatile prices in fossil fuels can affect the assurance of energy supply, the investments of policymakers, and the planning of short- and long-term measures (Ang et al., 2015; Vivoda, 2012). For this reason, energy-importing countries should prioritize enhancing their energy security.

Concerns are escalating regarding the consequences of GHG emissions from fossil fuels on the climate system (Zecca & Chiari, 2010). The term "global warming" refers to the climate impact caused by fossil fuels like oil, coal, and natural gas, as well as large-scale deforestation. The burning of fossil fuels releases large quantities of GHGs into the atmosphere, which increases heat on the planet's surface and drives climate change (Houghton, 2005).

Overall, renewable energy sources are often viewed as the first solution for preventing the destructive effects of rising global temperatures and climate change because renewables, especially solar and wind energy, are clean, green, and environmentally friendly. They do not emit carbon dioxide (CO2) or other GHGs into the atmosphere during consumption. In addition to their positive environmental contribution, renewable energies facilitate energy access in developing countries, thus helping to lower energy costs. Besides, it provides sustainability by meeting energy needs from domestic sources while reducing foreign dependence by diversifying resources. Moreover, renewable sources positively contribute to employment as a developing and growing sector.

Due to limited fossil fuel reserves, rapid depletion, and the privileges enjoyed by renewable sources, renewable energy investments are expanding daily. Numerous innovations are being implemented rapidly. Over the years, renewable energy sources will likely serve as the pioneer in ensuring the world's energy supply.

Solar Power

The conversion of the sun's heat into energy, which is then used to generate electricity or heat, is called solar energy. This is a significant source of inexhaustible energy across the globe (Kabir et al., 2018). Solar energy is produced in photovoltaics (PV) or concentrated solar power (CSP) systems. PV panels, which convert sunlight into electricity, are one of the most critical modern renewable energy technologies used on a personal or larger scale. CSP systems use mirrors to collect the sun's rays to generate thermal energy. Solar energy is one of the most environmentally friendly resources available, as it does not contribute to climate change unlike fossil fuels like coal and oil (Solangi et al., 2011). See Table 1.

Table 1. Annual solar energy potential (Goldemberg, 2000)

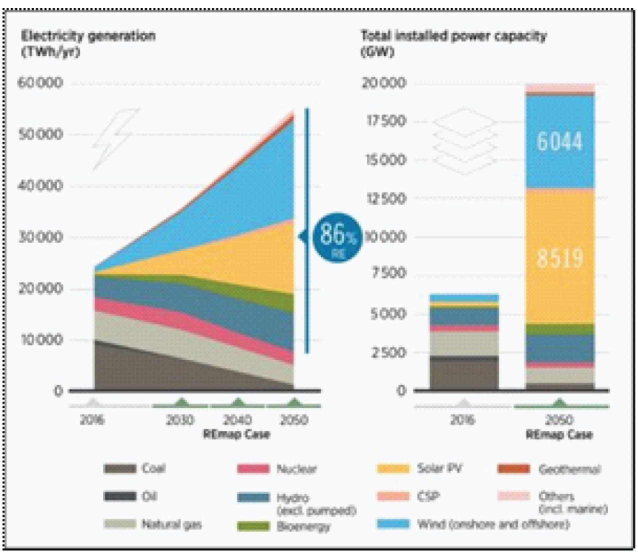
Region	Min. Exajoules [1]	Max. Exajoules
North America	181	7,410
Latin America and Caribbean	112	3,385
Western Europe	25	914
Central and Eastern Europe	4	154
Former Soviet Union	199	8,655
Middle East and North Africa	412	11,060
Sub-Saharan Africa	371	9,528
Pacific Asia	41	994
South Asia	38	1,339
Centrally planned Asia	115	4,135
Pacific OECD	72	2,263
TOTAL	**1,575**	**49,837**

Like other renewables, wind power is a clean, inexhaustible alternative to conventional energy sources. The main characteristics that make wind energy a highly valuable and practical resource are its low operating costs and extensive availability (Kumar et al., 2016). Wind power has been utilized for more than 3,000 years. Until the early 20th century, wind power provided mechanical strength, such as pumping water or grinding grain. With industrialization, wind energy was replaced by fossil-fueled engines or the electrical grid, which provided a more consistent power source. The oil price shock of the early 1970s, however, renewed interest in wind energy as an alternative to other fuels (Ackermann & Söder, 2000).

Wind energy can offer both direct (mechanical energy) and indirect (converting the wind's kinetic energy into electrical power) benefits. As the main component of the energy system, the turbine transforms wind energy into mechanical power usable in various applications. The initial turbine for wind electricity production was designed in the early 20th century (Kumar et al., 2016), and, due its vast potential, is one of today's most widely used alternative energy sources.

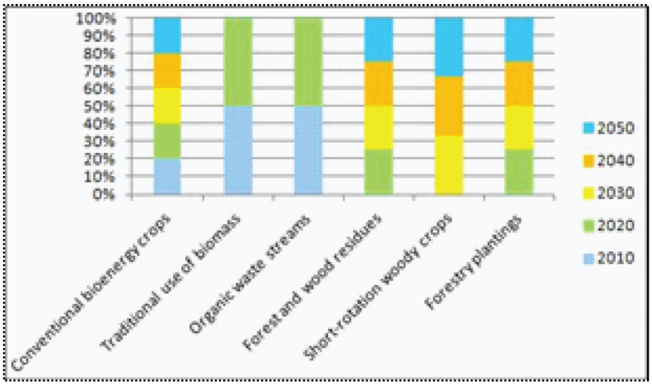
In addition to hydropower, wind energy is a crucial component of renewable energy as it is established worldwide and can be installed both offshore or on land (Sadorsky, 2009). Thus, wind power will lead a significant transition within the global electricity industry. By 2050, onshore and offshore wind will be the most prominent production source, providing more than one-third (35%) of the world's electricity demands (see Figure 1). Additionally, in the end-user sector, electricity consumption is expected to be higher than today's use (IRENA, 2019).

Figure 1. Wind and solar power dominate growth in renewable-based energy generation (IRENA, 2019)



Note: Electricity consumption by sector (TWh, %), electricity generation mix (TWh/yr) and power generation installed capacity (GW) by fuel, REmap Case, 2016-2050.

Figure 2. Global bioenergy supply in the net zero scenario (NZE), 2010-2050



Source: IEA analysis based on IIASA data.

Note: Organic waste agricultural residues include food processing and industrial and urban organic waste; they do not require a land area.

Biomass

Future economic development will require tremendous amounts of energy, as energy is a primary component of human activities (Joselin Herbert & Unni Krishnan, 2016). A sustainable energy supply is, therefore, one of our main challenges in the coming decades. With its considerable potential for growth in the production of thermal energy, electricity, and fuel for road transport, the world already views biomass as a significant renewable energy source capable of meeting future demands.

In fact, biomass is one of the first energy sources used by mankind, serving as a global fuel economy driver through the middle of the 18th century (Abbasi & Abbasi, 2010). Then, fossil fuels, which are energy-dense, were seen as a cleaner alternative to biomass, as they produced less pollution. However, interest in biomass energy has surged again because it is a carbon-neutral energy source, unlike fossil fuels, which release additional carbon into the atmosphere.

Biomass is the name of the plant matter in which solar energy transforms water and CO2 into organic matter by photosynthesis (Toklu, 2017). Biomass may be segregated by woody, non-woody, and animal wastes. Woody biomass includes forests, agro-industrial plantations, bush, urban, and farm trees. Non-woody biomass includes crop residues like straw, leaves, and plant stems, processing residues like sawdust, bagasse, nutshells, husks, or sewage-generated waste. The waste derived from animal dung is also animal waste (Mirza et al., 2008).

Biomass is a heterogeneous source that generates energy from numerous conversion processes, which distinguishes it from other renewable energy sources. In addition, biomass energy is categorized into two groups: modern and traditional (Toklu, 2017). Modern biomass, which is produced sustainably, is a substitute for conventional energy sources. It involves electricity and heat generation, transporting fuels from agricultural and forest residues and solid waste. Traditional biomass is produced unsustainably. It is seen as a resource for low efficiency, small-scale use like domestic activities (Goldemberg & Teixeira Coelho, 2004).

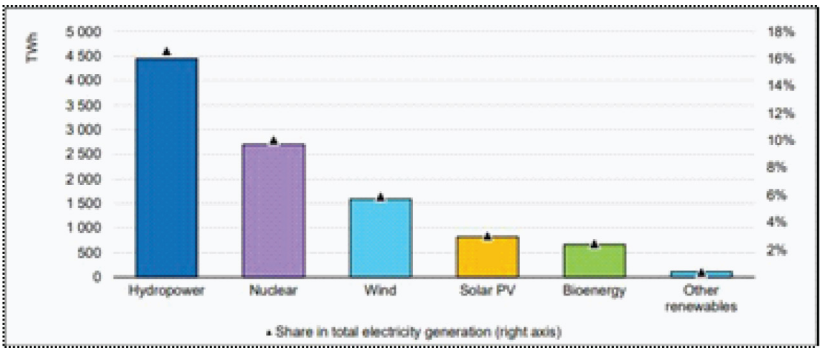
Hydropower

Hydropower is the electrical energy produced by taking advantage of the kinetic energy released by falling water, the only domestic energy source in many countries (Kaygusuz, 2010). The efficiency of many hydropower plants constructed in the early 20th century is still as high as 80% to 90%. In all hydroelectric power plants (HEPPs), the flowing water drives a turbine that converts the force of water movement into mechanical and electrical power (Egré & Milewski, 2002). Turbines convert the water pressure into mechanical shaft power to operate an electricity generator (Melikoglu, 2013). Thanks to this straightforward technique, it is an adaptable, effective, and dependable source of electricity (Egré & Milewski, 2002).

The water used for generating electricity in hydropower plants is not exhausted or consumed; it remains available for other use. In addition, it can finance infrastructures that support the well-being of people like irrigation systems for food production, water supply schemes, or eco-tourism through electricity-generated revenues (Yüksel, 2010). More than 150 countries generate hydroelectric energy and meet about 19.0% of the total electric power supply worldwide (Melikoglu, 2013).

For this reason, hydroelectric energy's role in electricity production is more remarkable than any other renewable energy technology. Figure 3 shows that hydroelectric energy technologies are the world's primary low-carbon source of global electricity production and produce more than all other renewable-based production combined.

Figure 3. Low-carbon electricity generation by technology, 2020



Source: IEA. Paris; 2020.

Additionally, hydropower technologies have been deemed cost-effective and environmentally sound for producing electricity (Edinger & Kaul, 2000). In countries with hydropower potential, the most prominent advantages of include relatively few GHG emissions and low-cost electricity generation (Evans et al., 2009; Melikoglu, 2013). Therefore, it has tremendous potential for further capacity expansion, reliability, and stability. For developing countries, hydropower's environmental and economic benefits will be significant in meeting tomorrow's energy demands (Kaygusuz, 2010; Yüksel, 2008).

Geothermal

As countries around the world research non-carbon renewable sources to reduce their dependence on fossil fuels (Aikins & Choi, 2012; Hepbasli & Ozgener, 2004; Zhu et al., 2015), geothermal energy (GE) stands out with compelling features compared to other renewables. It produces zero carbon emissions, uncommon detrimental effects, and uninterrupted power regardless of meteorological conditions (Templeton et al., 2014). For instance, solar energy production is limited to daylight hours and decreases with cloud cover. In the case of wind turbines, too, there is inherent variability in wind speeds.

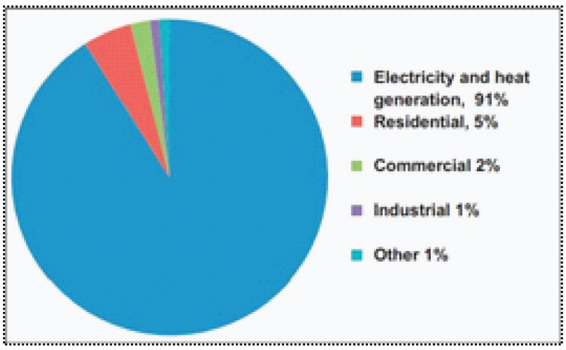
GE is a clean, renewable, and sustainable heat (thermal) source stored in the earth's interior, most often associated with tectonic and volcanic activities (Axelsson & Stefánsson, 2003). District heating, electricity production, and industry were the first sectors in the 20th century to use GE. In

1904, Prince Piero Ginori Conti built the first geothermal steam to generate power in Tuscany, Italy. The first large-scale district heating service was launched in Iceland in 1930.

Over the past 40 years, hundreds of megawatts (MW) have been directly used for electricity and power generation (Fridleifsson, 2001). Direct-use applications are one of the oldest, most adaptable, and most popular uses of geothermal resources (Dickson & Fanelli, 2003). Until recently, GE was not an essential source of electricity and heat generation globally, with a few exceptions like the United Staes, Indonesia, Iceland, and Italy (Bertani, 2012). By 2050, GE is expected to supply around 3% of the global electricity needs and 5% of the heating needs. This is a 0.1% increase in its share of the primary energy supply since 2008 (Shortall et al., 2015).

Figure 4 provides data on GE's overall use as a fuel source in the sector of transformation, conversion, and other sectors. The information is presented in a pie chart format, representing the percentage distribution based on data from 2007. It is measured in petajoules (Lund & Boyd, 2016).

Figure 4. World GE consumption by sector, 2007



Source: IEA. Paris; 2009.

RENEWABLE ENERGY RESOURCES IN TURKEY

Türkiye is a developing country where improving living conditions, economic growth, and industrialization are driving a significant increase in energy demand. Regarding fossil fuels, the country is rated poor, importing more than half of its energy requirements (Soydan, 2021). A shortage of supply and high levels of consumption have led to high import dependence and significant trade deficits. This points to the country's need for domestic renewable energy production. Turkey has the potential to generate renewable and sustainable energy rather than deplete its fossil fuels. Doing so will benefit the country, tapping into the diversification of energy resources (Bulut & Muratoglu, 2018).

Approximately 70% of Turkey's economic hydropower capacity, 8.9% of its wind power potential, 0.45% of its solar power potential, 30.7% of its geothermal potential, and 17.3% of its biomass potential have been used up (Bulut & Muratoglu, 2018; Ozcan, 2018). Although electricity generation technologies based on solar and wind energy have been influential in the energy sector, the leading renewable energy resources contributing to Turkey's energy mix are HEPPs, biomass for heating, and GE (Bulut & Muratoglu, 2018).

Regarding the National Renewable Energy Action Plan in Turkey, 61,000 MW of renewable energy will be installed by 2023, generating approximately 159 TWh. It is planned to produce 91,800 GWh of electricity annually from hydropower, 50,000 GWh from wind, and 8,000 GWh from solar energy, respectively (Ministry of Energy and Natural Resources [MENR], 2014). See Table 2.

Table 2. Electricity generation and installed capacity: 2013 data, 2023 forecast, and increases (MENR, 2014)

Renewable Energy Technologies	Installed Power Capacity (MW)			Electricity Generation (GWh)		
	2013	2023	Δ	2013	2023	Δ
Hydro	22.289	34.000	53%	59.420	91.800	54%
Wind	2.759	20.000	625%	7.558	50.000	562%
Geothermal	310	1000	223%	1.364	5.100	274%
Solar	0	5000	-	0	8.000	-
Biomass	224	1.000	346%	1.171	4.533	287%

Note: EJ = 1018, Joules (J) = 1015, kilojoules (kJ) = 24 million tonnes of oil equivalent (Mtoe).
Source: Ministry of Energy and Natural Resources (MENR, 2014)

Solar Energy in Türkiye

Turkey is geographically located to take advantage of solar energy (Benli, 2016), which is crucial when addressing global warming, reducing reliance on imported fossil fuels, and preserving resource diversity in power production (Soydan, 2021). It can harness solar energy with two leading technologies. First, solar PV converts sunlight into electricity with semiconductor materials. Second, using solar radiation, CSP systems heat receivers to high temperatures. Turbines or engines convert heat into mechanical energy, ultimately converting heat into electricity (Topkaya, 2012).

Prior to 2014, Turkey used some solar energy to obtain hot water in homes and industries, including drying products and related applications (Bulut, 2021). Due to cost reductions in PV module unit prices worldwide, legal regulations, and incentives, as well as the competitive nature of solar power plant installations, Turkey's first solar power plants began to generate electricity in 2014. Since this transition, there has been a noticeable increase in the installed capacity of solar energy systems and the number of power plants (Bulut, 2021)

According to the "World and Turkey's View of Energy and Natural Resources" report published by the MENR, solar energy contributed just 0.01% to Turkey's total electricity production in 2014, generating 17.4 GWh out of 251.963 GWh. By 2016, this share increased to 0.36%, with solar power production reaching 972 GWh out of 273.387 GWh (Soydan, 2021). The total installed solar power plant capacity, which increased rapidly between 2014 and 2018, reached a near standstill in mid-2019 due to the cancellation of land support for unlicensed power plants, a decrement in incentive coverage, and an excessive exchange rate increase (Çeçen et al., 2022). As of the end of June 2022, the installed electricity capacity of Turkey based on solar energy was 8,479 MW. The ratio of this power to the total installed capacity was 8.35% (Pwc Turkey, 2023).

In 2023, Turkey planned to meet 30% of its electricity consumption demand from renewable energy sources. In the field of solar energy, an installed power capacity of approximately 5,000 MW was targeted at the end of that same year.

While PV technology, which uses solar energy to generate electricity, is widely used in Turkey, the development of the CSP technology is ongoing. Thermal power generation from solar energy is also involved. Turkey, which has high solar values, should use this potential to generate electricity, including solar power plants based on solar cells and other technologies that use solar energy (Bulut, 2021).

Wind Power in Turkey

Turkey has strong wind energy potential due to its geographical features, with seas on three sides and mountains across much of the country that boast regular and moderate airflow through their valleys. Türkiye's wind resources are concentrated in the country's western and southern regions.

Additional wind plants can be installed on both onshore and offshore sites (Erdogdu, 2009). Compared to land power plants, offshore wind power plants are expensive. However, they offer benefits like continuity and energy efficiency (Kabak & Akalın, 2022). To make offshore wind energy investments viable and attractive, it will be necessary to amend the renewable energy resources law in Turkey. The government should also implement financial incentives and public funding throughout in EU countries to promote offshore wind energy projects in Turkey (Satir et al., 2018).

In 1986, with a nominal wind energy capacity of 55 kW, Izmir was the first city in Turkey to successfully produce electricity for general use from wind power. However, Turkey's use of wind energy has increased since installing its first wind power plant, with a total capacity of 1.5 MW in 1998 (Erdogdu, 2009). As to the country's "Wind Energy Statistic Report," the total installed wind power reached 11.641 MW, with 540 MW commissioned in the first six months of 2022. In the first half of 2022, 10.72% of the total electricity generated in Turkey was obtained from wind, while 11.67% of the electricity in March was provided by wind (Turkish Wind Energy Association, 2023).

Biomass in Turkey

Biomass energy is the use of organic materials—such as wood, animals, and plant waste—to produce energy. This energy is used to generate electricity, heat houses, fuel vehicles, and supply process heat for industrial operations (Toklu, 2017). Hence, the energy stored in biomass is also termed "bioenergy" (Bilgen et al., 2015).

Biomass is the primary energy source in rural Turkey (Toklu, 2017). Sources include wheat straw, timber, and wood materials like cocoons, waste shells, hazelnuts, grain dust, and residues from crops or fruit trees (Bilgen et al., 2015). The province of Adana has a 45 MW installed capacity, making it the first project in Turkey to generate electricity from biomass (Melikoglu, 2013). The installed capacity based on biomass and waste heat energy is 2.172 MW as of June 2022. The ratio of total installed capacity is 2.14%. By 2030, the electrical generation capacity from biomass is estimated to reach approximately 50 GW (Republic of Turkey, Energy and Natural Resources Ministry, 2023; Toklu, 2017)

Hydropower in Turkey

One of the world's largest potential sources of hydropower is in the Middle East. Turkey's Black Sea coastline, characterized by its steep and treacherous terrain, holds substantial potential for hydropower generation, particularly in the Eastern Black Sea region (Kucukali & Baris, 2009).

Turkey's first hydroelectric power generation started in 1902 with a micro-scale HEPP of 60 kW in Tarsus. The total installed capacity was 30.000 kW, the production was 45 GWh/year, and electricity was available only in Istanbul, Adapazarı, and Tarsus. By 1950, only 18 MW of the power plants with a total installed capacity of 408 MW belonged to hydro. In 1954, State Hydraulic Works, responsible for waterworks, was established, and hydropower generation was added to its responsibilities (Kankal et al., 2014).

In 2003, several HEPPs were built in Turkey due to the Water Usage Rights Agreement, permitting the private sector to invest in energy (Peçe et al., 2023). Electricity generation, in turn, nearly tripled since 2000. Thus, the long-term trend toward hydropower increased. However, the availability of hydropower depends on hydrological conditions, which can vary significantly. For example, a sudden decline in production in 2014 resulted from a drought experienced that year.

The contribution of hydropower to Turkey's electricity supply was 29% in 2019. According to data supplied by the Turkish government, as of May 2020, hydropower has been the most significant source of electricity generation, accounting for 34% of all electricity generation. By the end of 2023, the hydropower capacity was projected to reach 32.000 MW based on projects under construction (IEA, 2021). Additionally, the Energy Market Regulatory Authority created two scenarios based on data from the hydropower plants' commissioning years, installed capacity, and progress rate. The installed hydropower capacity and hydroelectricity generation forecasts between 2012 and 2021 were predicted by the Turkish Electricity Transmission Company (TEIAS) using these Energy Market Regulatory Authority scenarios. See Table 3.

Table 3. Turkey's installed hydropower capacity and hydroelectricity generation projections: Based on two scenarios, 2012 and 2021 (TEISA, 2012)

Year	Scenario 1		Scenario 2	
	Installed capacity, MW	Electricity generation, GWh	Installed capacity, MW	Electricity generation, GWh
2012	20.470	65.463	19.667	64.158
2013	21.461	72.934	20.893	70.698
2014	24.291	79.651	23.085	76.555
2015	28.003	90.522	25.883	84.380
2016	31.606	104.443	29.143	96.511
2017	33.394	112.708	31.706	106. 626
2018	33.815	115.779	33.815	113.652
2019	33.815	116.558	33.815	116.558
2020	33.815	116.558	33.815	116.558
2021	33.815	116.558	33.815	116.558

Source: Turkish Electricity Energy Transmission Company (TEIAS) 2012.

Geothermal in Türkiye

Turkey is on an active tectonic belt, placing it in a prosperous global position regarding GE (Republic of Turkey, Energy and Natural Resources Ministry, 2023). GE is currently used for electricity generation and direct use in Turkey (Tut Haklıdır, 2015). Direct-use applications first appeared in 1986, while GE applications first appeared in 1984 (Mertoglu et al., 2015).

Western Anatolia is home to the country's most extensive enthalpy geothermal reserves. As a result, geothermal power production projects have been implemented since 1984 (Tut Haklıdır, 2015). Geothermal district heating systems increased up to 2000; however, applications for generating GE remained fixed at 15 MW until 2007.

The Turkish private sector invested in geothermal power generation after issuing regulations on geothermal and renewable energy that provided incentives for producing electricity from renewable sources. Using this method, the amount of geothermal power produced since 2007 has reached 400 MW (Mertoglu et al., 2015). As of 2021, Turkey ranked second in the number of geothermal power units and fourth globally in installed power capacity due to its exponential growth over the last 15 years (Serpen & DiPippo, 2022).

The installed capacity based on GE was 1.686 MW as of June 2022, while the geothermal power capacity target for 2030 is 4000 MW (Republic of Turkey, Energy and Natural Resources Ministry, 2023). Turkey's non-hydro renewable installed capacity increased significantly over the past few decades due to government support, primarily through renewable energy-supporting mechanisms (PwC Turkey, 2021). See Figure 5.

Figure 5. Global installed capacity rankings for Turkey

Development of Non-Hydro Renewables	December 2007		August 2021	% of Total Capacity as of August 2021
Wind Large amount of investments due to attractive FiT Schemes under YEKDEM	148 MW	➡	10,014 MW	10.2%
Solar Strong growth in the past few years, mainly attributable to unlicensed generation	0 MW	➡	7,435 MW	7.5%
Geothermal High number of geothermal sources in Turkey which can be utilized for generation	23 MW	➡	1,650 MW	1.7%
Biomass Less interest due to high CAPEX and dependency on external source factors (waste collection).	21 MW	➡	1,813 MW	1.8%

Source: PwC Türkiye, 2021.

LITERATURE REVIEW

Technological innovations lower costs and increase the use of renewable energy sources in many countries. However, transitioning to efficient, modern, and low-carbon energy systems at the least possible cost requires technological innovation. Infrastructures that link supply and demand technologies are also a part of energy systems. Technologies that make renewable energy more accessible are beneficial for all sectors. It is generally accepted that technological advancement in any country is essential for renewable energy production and consumption to be put into practice. Renewable energy production requires improved technologies, which could result in lower external costs and less environmental harm (Alam & Murad, 2020).

This study explores the relationship between technological innovation and renewable energy production, as well as economic growth represented by the gross domestic product (GDP). The technology innovation-RE production nexus is the first focus of the research subcategory. For example, using panel regression models, Popp et al. (2011) examined the mechanism influencing technological innovation using renewable energy technology patents as a proxy for renewable energy investment in 26 Organisation for Economic Co-Operation and Development (OECD) countries between 1991 and 2004. Despite its small effect, they discovered that technological innovation could encourage investments in renewable energy.

Aflaki et al. (2014) examined the diffusion of renewable energy technologies in 15 EU countries between 1990 and 2012. Using different panel data estimators, they argued that technological innovation positively impacts the spread of renewable energy. The study, led by Benson and Magee (2014), examined two pairs of renewable energy technologies. It reveals that the annual improvement rate of cost and investment differs within the four technological areas, including solar PV, wind turbines, batteries, and capacitors. Irandoust (2016) used a vector autoregression (VAR) model to examine the relationship between renewable energy consumption, technological innovation, economic growth, and CO_2 emissions in the Nordic nations between 1975 and 2012. The results show that technological innovation and renewable energy have a one-way causal relationship.

Bamati and Raoofi (2020) found that the factors influencing the use of renewable sources differ depending on income level using the generalized least square panel data estimate method. The findings show that high-technology export in developed nations considerably impacts renewable energy production. However, high technology export for renewable energy resource utilization in developing countries is not statistically significant. Zheng et al. (2021) examined the impact of renewable energy technological innovation on renewable energy generation by nonspatial and spatial econometric models based on a panel dataset covering 30 provinces in China between 2005 and 2017. On average, a 1% increase in the level of technological innovation of renewable energy in each province leads to a 0.411% increase in the production of renewable energy directly and a 3.264% increase in the production of renewable energy in its neighboring provinces through technology.

Khan et al. (2022) revealed the relationship between technological innovation and renewable energy in Germany. The findings of the whole sample causality demonstrate that technological innovation substantially influences renewable energy. The rolling window method examines the causal relationship between technological innovation and renewable energy while considering structural changes. The results demonstrate that technological innovation affects renewable energy favorably and unfavorably across various sub-samples.

Numerous studies are interested in the nexus between GDP and energy consumption, with many studies conducted in the EU and around the world. They often share the long-term causality correlations between energy sources and economic growth reported in the literature. As explained in the review, the two parameters in question are related, with a strong movement toward renewable energy sources in countries that rely on foreign energy. Utilizing renewable energy in production has equaled labor and capital's importance (Abdullah et al., 2020).

The second part of the study examined the link between renewable energy production and economic growth or GDP. Such a study shows that significant renewable energy is needed for strong economic growth. Renewable energy development and economic growth nexus have been examined in several studies under four testable hypotheses (Tugcu et al., 2012; Yoo & Kwak, 2010).

At first, the uni-directional causality from energy production or growth hypothesis argues that renewable energy consumption significantly impacts economic growth.

The second hypothesis—the bi-directional causality or feedback hypothesis—asserts that renewable energy consumption and economic growth are interdependent. Consequently, rising real GDP results from increased energy consumption, in turn, positively impact energy consumption across the nation. The economic stimulus measures in this situation will boost the GDP and raise energy consumption.

The third, known as the non-causality hypothesis or neutrality hypothesis, contends that there is no econometrical dependency on the relationship between renewable energy consumption and the production of final goods in an economy. This is the case in nations where the service sector, which has low energy consumption, accounts for a more significant portion of real GDP growth. Namely, the economy is decoupled from the dynamics of energy consumption.

The last hypothesis—the unidirectional causality from economic growth or conservation hypothesis—argues that growth in real GDP impacts renewable energy consumption. In this instance, cutting back on energy consumption will only have a marginal effect on the dynamics of an economy.

The conservation hypothesis can be examined in the context of increased energy consumption brought on by economic activity and decreased consumption. This is brought on by economic activity due to restrictions on resource use and reduced demand for products with high energy consumption (Marinaş et al., 2018).

The growth hypothesis refers to the fact that energy consumption as a complement to labor and capital in producing goods and services contributes directly and indirectly to economic growth. There is a one-way (uni-directional) causal relationship between energy consumption and economic growth, meaning that rising energy consumption would inevitably result in rising economic growth (Payne, 2009).

The feedback hypothesis means that economic growth and energy consumption are mutually correlated. The hypothesis is supported if there is bi-directional causality between energy consumption and economic growth (Tugcu et al., 2012).

The neutrality hypothesis states that energy consumption does not impact economic growth. The lack of a causal relationship between energy consumption and economic growth supports the neutrality hypothesis (Tugcu et al., 2012).

Within the conservation hypothesis, a decrease in energy consumption has little or no effect on economic growth. Causality is assumed to be uni-directional (Sadorsky, 2009).

DATA ANALYSIS AND FINDINGS

This study aims to measure the contribution of technological developments toward Turkey's renewable energy production. It uses annual time series data on Turkey from 1980-2022 to investigate the causal relationship between technology and renewable energy production. Data from technological development cannot be obtained monthly or quarterly, so annual data are used for this study.

All data used in econometric analyses were obtained from the Turkish Statistical Institute Website, the Republic of Turkey MENR, and the World Bank. Econometric analysis was performed using the EViews 11 package program. According to the OECD, research and development (R&D) and patent registrations are associated with many other activities with scientific and technological foundations. Therefore, this study uses total R&D expenditures and patent registrations to represent technological development.

GDP change is one macroeconomic data showing that the country's economy has grown or contracted. For that reason, GDP is used as an indicator of economic growth. GDP was used as the control variable.

The logarithm of the variables was part of the analysis in this study. L indicates that a logarithm of the variable is used. The variable definitions used in the study are given in Table 4.

Table 4. Variable definitions

LRD	Real Total R&D Expenditures
LGDP	Real Gross Domestic Product
LPATENT	Patent Registrations
LRENEW	Renewable Energy Production (GWh)

The empirical model established in the study is: LRENEW = f (LRD, LPATENT, LGDP).

Table 5. The flow chart of the study is as follows:

DATA COLLECTION			
Annual Data (1980-2022)			
↓			
TRADITIONAL UNIT ROOT TESTS			
ADF	Phillips-Perron (PP)	Kwiatkowski-Phillips-Schmid t-Shin (KPSS)	Ng-Perron Test
Stationary (NO)		**Stationary (YES)**	
↓			
VAR MODEL			
Determination of VAR Lag Length			
Identification Tests			

continued on following page

Table 5. Continued

DATA COLLECTION		
Autocorrelation LM	White Heteroscedasticity Test	Inverse Roots of AR Characteristic Polynomial
Structural Consistency (NO) Stop Analysis		**Structural Consistency (YES)**
↓		
JOHANSEN-JUSELIUS COINTEGRATION TEST		
Cointegration (NO) Stop Analysis		**Cointegration (YES)**
		VECTOR ERROR CORRECTION MODEL (VECM) Aim: Finding the source of the causality. **VECM Granger Causality/Block Exogeneity Wald test** Short-run relationship between variables **Causality** ↓ **CONCLUSION** ***In the Short Run*** *Technological Developments (DLRD & DLPATENT)* *Renewable Energy Production (DLRENEW)* *Economic Growth (DLGDP) Renewable Energy Production (DLRENEW)* *Economic Growth (DLGDP) Patent Registrations (DLPATENT)* ***In the Long Run*** *Technological Developments (LRD & LPATENT) Renewable Energy production (LRENEW)*

In the study, traditional unit root tests were applied to determine whether the series to be used in the study were stationary. Then, the lag lengths of the VAR model to be established were determined. The next stage performed the identification tests of the established model. After determining the appropriate VAR model, cointegration analysis was performed to identify whether there was a long-term relationship between the variables. The last VECM test was applied to determine the causality relationship and direction between the variables.

First, ADF (1981), PP (1988), KPSS (1992), and Ng-Perron (2001) traditional unit root tests were applied to check if the series was stationary. Schwarz Information Criterion (SIC) was used to determine the lag length during the unit root tests. Table 6 shows the ADF and PP unit root test results for the variables used in this study, in which the values in parentheses indicate the lag length. The results of the ADF and PP unit root tests applied on the levels of the variables show that the variables are not stationary while their first-degree differences are, indicating that the difference of the variables is stationary.

Table 6. ADF and PP unit root test results

ADF Test Statistics					
Variable	**Constant**	**P-values**	**constant and trend**	**P-values**	**Result**
LRD	1.004995 (0)	P = 0.9959	-1.299261 (0)	P = 0.8745	not stationary
LGDP	-1.370543 (1)	P = 0.5872	-1.304075 (1)	P = 0.8729	not stationary

continued on following page

Table 6. Continued

ADF Test Statistics					
Variable	**Constant**	**P-values**	**constant and trend**	**P-values**	**Result**
LPATENT	-0.944375 (0)	P = 0.7640	-2.672996 (0)	P = 0.2524	not stationary
LRENEW	0.690420 (0)	P = 0.9905	-3.035160 (1)	P = 0.1355	not stationary
DLRD	-6.479368 (0)	P = 0.0000	-6.838302 (0)	P = 0.0000	Stationary
DLGDP	-3.785216 (0)	P = 0.0062	-3.894038 (0)	P = 0.0023	Stationary
DLPATENT	-9.497653 (0)	P = 0.0000	-9.386754 (0)	P = 0.0000	Stationary
DLRENEW	-3.762998 (1)	P = 0.0066	-3.575682 (1)	P = 0.0249	Stationary
PP Statistics					
Variable	Constant	P-values	constant and trend	P-values	Result
LRD	1.347741 (2)	P = 0.9985	-1.299261 (0)	P = 0.8745	not stationary
LGDP	-1.229382 (4)	P = 0.6528	-1.210602 (4)	P = 0.8953	not stationary
LPATENT	-0.724291 (2)	P = 0.8295	-2.729244 (4)	P = 0.2307	not stationary
LRENEW	0.563483 (3)	P = 0.9870	-3.241861 (3)	P = 0.0903	not stationary
DLRD	-6.479368 (0)	P = 0.0000	-6.838302 (0)	P = 0.0000	Stationary
DLGDP	-3.844289 (3)	P = 0.0052	-3.877905 (2)	P = 0.0221	Stationary
DLPATENT	-9.582995 (2)	P = 0.0000	-9.478775 (2)	P = 0.0000	Stationary
DLRENEW	-7.143617 (3)	P = 0.0000	-7.430388 (3)	P = 0.0000	Stationary

Note: A p-value > 0.05 indicates unit root is detected (not stationary); otherwise, it means there is no unit root (stationary). The first difference is shown by using the "D" used in front of the variables.

Next, the KPSS test is performed to show that the difference of series is stationary. Table 6 displays the results of the test.

According to Table 7, the LM test statistics for the levels of the variables are not stationary as they are greater than the KPSS test critical values (at a 5% significance level). Thus, they contain unit roots while the results obtained by applying the same test to the first-order difference of the variables show that the difference of the variables is stationary. The results of the KPSS test support findings and are consistent with ADF and PP test results. The Ng-Perron (2001) unit root test was performed after ADF, PP, and KPSS unit root tests. The Ng-Perron unit root test results are shown in Table 8.

Table 7. KPSS test results

Variable	LM-Stat Constant	Asymptotik Critical Value (5%)	LM-Stat Constant and Trend	Asymptotik Critical Value (5%)	Result
LRD	0.821444	0.463000	0.186387	0.146000	not stationary
LGDP	0.740728	0.463000	0.166437	0.146000	not stationary
LPATENT	0.754602	0.463000	0.155312	0.146000	not stationary
LRENEW	1.084365	0.463000	0.198086	0.146000	not stationary
DLRD	0.272360	0.463000	0.102219	0.146000	Stationary

continued on following page

Table 7. Continued

Variable	LM-Stat Constant	Asymptotik Critical Value (5%)	LM-Stat Constant and Trend	Asymptotik Critical Value (5%)	Result
DLGDP	0.171991	0.463000	0.083344	0.146000	Stationary
DLPATENT	0.070412	0.463000	0.069723	0.146000	Stationary
DLRENEW	0.312219	0.463000	0.107536	0.146000	Stationary

The null hypotheses of MSB and MPT tests indicate that the series is stationary, whereas the null hypotheses of MZa and MZt tests show that the unit root is in the series. The Ng-Perron test was analyzed by Spectral OLS-Detrented AR. Optimal lag lengths were found with SIC. In Table 8, series I (1) is the first aware station because the MZa and MZt values in the first differences of the series are greater than the table value, and the MSB and MPT values are smaller than the table value.

Table 8. Ng-Perron test results

	Constant				Constant+Trend			
Variable	MZ_a	MZ_t	MSB	MPT	MZ_a	MZ_t	MSB	MPT
LRD (0)	3.95358	1.64835	0.41693	24.7523	-8.40711	-1.54099	0.18330	12.2852
LGDP (1)	-0.00999	-0.00663	0.66390	28.3746	-13.8144	-2.57376	0.18631	6.90634
LPATENT (0)	0.42143	0.23521	0.55813	23.8966	-10.9641	-2.33957	0.21339	8.32027
LRENEW (1)	1.24236	1.18618	0.95478	66.9925	-3.59619	-1.31022	0.36433	24.8332
DLRD (0)	-20.4810	-2.13293	0.15622	1.19844	-20.2901	-3.17318	0.15639	4.56348
DLGDP (0)	-15.8622	-2.81530	0.17749	1.54799	-18.2888	-2.95366	0.16519	5.39543
DLPATENT (0)	-18.6594	-3.04471	0.16317	1.34818	-17.8312	-2.98564	0.16744	5.11198
DLRENEW (1)	-8.25780	-1.99145	0.20459	3.11287	-17.9085	-2.97319	0.14950	4.56281
Asymptotic critical value 5%	-8.10000	-1.98000	0.23300	3.17000	-17.3000	-2.91000	0.16800	5.48000

Note: () indicates lag length.

As all the variables included in the model are observed to be stationary at first degree, cointegration analysis can be performed together with vector autoregressive (VAR) analysis. The most crucial condition in VAR analyses is the accurate estimation of the VAR lag length as determined by the information criteria. Table 9 shows the determination of the VAR lag length.

Table 9. Determination of VAR lag length

Lag	LR	FPE	AIC	SIC	HQ
0	NA	8.395689	13.47918	13.64807	13.54025
1	303.2407	0.003244	5.615166	6.803717	5.920488

continued on following page

Table 9. Continued

Lag	LR	FPE	AIC	SIC	HQ
2	**35.07465***	**0.002390***	**5.283725***	**6.459605***	**5.833306***
3	15.76864	0.003170	5.499701	7.695245	6.293541

*Indicates lag order selected by the criterion
LR: sequential modified LR test statistic (each test at 5% level)
FPE: Final prediction error, AIC: Akaike information criterion, SIC: Schwarz Information Criterion
HQ: Hannan-Quinn information criterion

As indicated in Table 9, LR, FPE, AIC, SIC, and HQ information criteria indicate two lag lengths. In the first case, identification tests were carried out on a two-year lag VAR model. The LM test has been applied to determine whether there is an autocorrelation problem at a specified number of lags. When the probability values in Table 10 are considered, the null hypothesis that "there is no autocorrelation" problem in the second lag is accepted. Furthermore, to test the variance problem, the white heteroscedasticity test has been applied. The H_0 hypothesis in the variance test is "there is no variance."

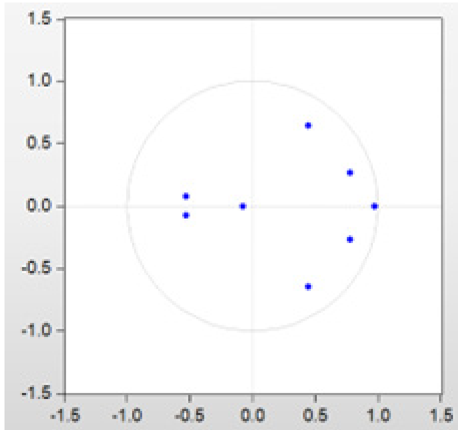
Table 10. Autocorrelation LM and white heteroscedasticity test results

Autocorrelation LM Test Results		
Lags	**LM-Stat**	**Prob**
1	13.92946	0.6067
2	20.27552	0.9492
White Heteroscedasticity Test Results		
	Test Statistics	Prob
2	18.76983	0.2808

As a result of the variance test result, it is accepted that there is no variance problem between error terms at a 5% significance level. Consequently, it was concluded that the VAR analysis contains no autocorrelation and variance problem in which two lags were considered.

Investigating whether the two-lag VAR model remains stable is the next step in this study. The position of the reverse roots of the autoregressive characteristic polynomial of the model within the unit circle gives information about the stability of the model.

Figure 6. Inverse roots of AR characteristic polynomial



None of the opposite roots of the AR characteristic polynomial are located outside the unit circle, as shown in Figure 6, indicating that the established VAR model is stable. After completing the analysis related to the structural consistency of the VAR analysis, Johansen-Juselius (JJ) (1990) test is used for co-integration analysis, and the results are given in Table 11. According to Table 11, trace and maximum eigenvalue test statistics reject the null hypothesis, which claims the absence of no co-integration, and one co-integration relation is found in the model. In other words, this study has a long-run relationship between technological development and renewable energy.

Table 11. Johansen-Juselius test results

Unrestricted Cointegration Rank Test (Trace)				
Hypothesized		**Trace**	**0.05**	
No. of CE(s)	Eigenvalue	Statistic	Critical Value	Prob.**
None *	0.605145	69.58841	63.87610	0.0153
At most 1	0.345420	32.41889	42.91525	0.3661
At most 2	0.195519	15.46843	25.87211	0.5358
At most 3	0.155621	6.766130	12.51798	0.3695
Trace test indicates 1 cointegrating eqn(s) at the 0.05 level				
* denotes rejection of the hypothesis at the 0.05 level				
**MacKinnon-Haug-Michelis (1999) p-values				
Unrestricted Cointegration Rank Test (Maximum Eigenvalue)				
Hypothesized		Max-Eigen	0.05	
No. of CE(s)	Eigenvalue	Statistic	Critical Value	Prob.**
None *	0.605145	37.16952	32.11832	0.0110
At most 1	0.345420	16.95047	25.82321	0.4619
At most 2	0.195519	8.702296	19.38704	0.7546
At most 3	0.155621	6.766130	12.51798	0.3695

continued on following page

Table 11. Continued

Unrestricted Cointegration Rank Test (Trace)				
Hypothesized		**Trace**	**0.05**	
Max-eigenvalue test indicates 1 cointegrating eqn(s) at the 0.05 level				
* denotes rejection of the hypothesis at the 0.05 level				
**MacKinnon-Haug-Michelis (1999) p-values				

To see these long-run relationships, the normalized equation is examined. The normalized equation is interpreted according to a 5% significance level.

Normalized equation according to LRENEW:

$$\underset{(t-value)}{LRENEW} = \underset{(4.5944)}{0.4482} + 2.2904\underset{(5.2148)}{LGDP} + 2.5101\underset{(8.0154)}{LPATENT} + 10.0691\underset{(2.3574)}{LRD} \quad (1)$$

When the normalized equation is analyzed, it is seen that there is a significant positive relationship between technological development and renewable energy in the long run. In other words, renewable energy production increases as long as total R&D expenditures and patent registrations increase. Therefore, in the long run, technological developments are an important factor in renewable energy production in Turkey.

The long-run relation among the variables enables the establishment of a VECM that includes the error correction term obtained through co-integration regressions and, thus, is aimed at finding the source of the causality.

The VECM equations established in the study are:

D

$$D(LRENEW)t = c_1 + a_1\, ECT_{t-1} + b_1\, D(LRENEW)_{t-1} + d_1\, D(LRENEW)_{t-2} + e_1\, D(LGDP)_{t-1} + f_1\, D(LGDP)_{t-2} + g_1\, D(LPATENT)_{t-1} + h_1\, D(LPATENT)_{t-2} + j_1\, D(LRD)_{t-1} + k_1\, D(LRD)_{t-2} + u_t \quad (2)$$

Table 12 provides the VECM's test results.

Table 12. VECM test results

	(1)	(2)	(3)	(4)
	D(LRENEW)	D(LPATENT)	D(LRD)	D(LGDP)
ECT(-1)	**-0.416102**	-0.170042	-0.126583	-0.080786
	[-4.12922]	[-0.75349]	[-0.13827]	[-1.17618]
D(LRENEW(-1))	-0.203983	0.046339	0.157505	-0.019080
	[-1.70066]	[0.17251]	[0.14455]	[-0.23338]
D(LRENEW(-2))	0.121051	-0.024822	-0.029439	0.036718
	[0.97057]	[-0.08887]	[-0.02598]	[0.43192]
D(LPATENT(-1))	-0.178506	-0.810113	-0.755660	-0.065730

continued on following page

Table 12. Continued

	(1)	(2)	(3)	(4)
	[-1.35663]	[-2.74922]	[-0.63216]	[-0.73290]
D(LPATENT(-2))	-0.145518	-0.318669	-0.906767	-0.006148
	[-1.60612]	[-1.57057]	[-1.10166]	[-0.09956]
D(LRD(-1))	**0.112434**	0.045289	-0.004069	0.024430
	[3.21071]	[0.57749]	[-0.01279]	[1.02352]
D(LRD(-2))	-0.043968	0.074844	-0.225513	-0.222376
	[-0.23898]	[0.18165]	[-0.13493]	[-1.77335]
D(LGDP(-1))	**0.701821**	-1.814522	-0.149349	0.340116
	[2.15377]	[-2.48651]	[-0.05045]	[1.53135]
D(LGDP(-2))	-0.315149	-0.917094	-1.643249	0.224311
	[-1.04129]	[-1.35308]	[-0.59765]	[1.08737]
C	0.269352	0.540073	1.061613	0.103323
	[3.07947]	[2.75716]	[1.33602]	[1.73311]
R-squared	0.813053	0.440315	0.055626	0.405137
Adj. R-squared	0.696969	0.272409	-0.227686	0.226678
F-statistic	20.28110	2.622393	0.196341	2.270194

t-statistics in [ ], 5% significance level

ECT (-1), the long-run co-integration-related error correction term, shows the size of the past imbalance. The error correction coefficient is expected to be negative and statistically significant. According to the test results of the VECM, the error correction coefficient is negative and statistically significant at the 5% significance level for column 1. According to column 1, a long-run causal relationship exists between total R&D expenditures and patent registrations to renewable energy production. R^2 = 0.813053 for column 1, so the interpretation is consistent. This result supports the result obtained from the JJ cointegration test. The causality from technological developments to renewable energy production supports the results obtained from the normalized Equation 1.

According to column 1, the effect of one-period lagged total R&D expenditure on renewable energy production is positively significant *(coefficient=0.112434, t-value =3.21071).* Again, according to column 1, the effect of one-period lagged real GDP on renewable energy production is positively significant *(coefficient=0.701821, t-value =2.15377).* Although the error correction terms in columns 2, 3, and 4 have a negative sign, they are not statistically significant. Therefore, they were excluded from the analysis.

The short-run relationship between variables is explored in the next stage. For that purpose, the VECM Granger Causality/Block Exogeneity Wald test is performed. The results are shown in Table 13.

Table 13. VECM Wald test results

Dependent variable: D(LRENEW)		
Excluded	**Chi-sq**	**Prob.**
D(LPATENT)	12.747045	0.0253
D(LRD)	10.52551	0.0052
D(LGDP)	5.481705	0.0445
Dependent variable: D(LPATENT)		
Excluded	Chi-sq	Prob.
D(LRENEW)	0.043321	0.9786
D(LRD)	0.353502	0.8380
D(LGDP)	7.649611	0.0218
Dependent variable: D(LRD)		
Excluded	Chi-sq	Prob.
D(LRENEW)	0.023248	0.9884
D(LPATENT)	1.226330	0.5416
D(LGDP)	0.357439	0.8363
Dependent variable: D(LGDP)		
Excluded	Chi-sq	Prob.
D(LRENEW)	12.27809	0.0470
D(LPATENT)	0.785099	0.6753
D(LRD)	14.46939	0.0107

5% significance level

According to Wald test results, there is a causality relationship between total R&D expenditures and patent registrations to renewable energy production in the short run. According to this result, technological developments affected renewable energy production in the short run. It is observed that the short-term findings correspond to those found in the long term. In addition, the study concluded that there is a bi-directional causality relationship between renewable energy production and economic growth in the short run. In addition, there is a short-term causality relationship from economic growth to patent registrations, which is one of the representative variables of technological development.

Table 14. Causality

Short Run		
Technological Developments (DLRD & DLPATENT)	→	Renewable Energy Production (DLRENEW)
Economic Growth (DLGDP)	↔	Renewable Energy Production (DLRENEW)
Economic Growth (DLGDP)	→	Patent Registrations (DLPATENT)

continued on following page

Table 14. Continued

Short Run		
Long Run		
Technological Developments (LRD & LPATENT)	→	Renewable Energy production (LRENEW)

CONCLUSION

Global concern for sustainable development has accelerated a shift toward renewable energy (Bhattacharya et al., 2016). Increasing the use of renewable energy is crucial for all countries, especially developing ones due to considerable increases in energy demand and CO2 emissions. Renewables can play a vital role in reducing the global dependence on fossil fuels and minimizing GHG emissions to address climate change challenges (Bamati & Raoofi, 2020).

There is significant potential for Turkey to generate, use, and exploit renewables (Bulut & Muratoglu, 2018). This study aims to measure the contribution of technological developments to renewable energy production in Turkey. Through annual time series data on Turkey from 1980-2022, the study investigates the causal relationship between technology and renewable energy production. It applies ADF (1981), PP (1988), KPSS (1992) and Ng-Perron (2001) tests for data analysis. The study shows a significant positive relationship between technological development and renewable energy production in the long run. In other words, renewable energy production increases as long as total R&D expenditures and patent registrations increase. Therefore, technological developments are an essential factor in renewable energy production in Turkey.

In the short-term, there is a causality relationship between total R&D expenditures and patent registrations for renewable energy production. It can also be said that technological developments affect renewable energy production in the short run. The short-term findings correspond to those found in the long term.

In addition, the study concludes that there is a bi-directional causality relationship between renewable energy production and economic growth in the short run. Although, the study mirrors the feedback hypothesis results in the literature review, it differs regarding renewable energy consumption. In addition, there is a short-term causality relationship between economic growth and patent registrations, which is one of the representative variables of technological development. The findings obtained from this study support the findings of the studies conducted by Aflaki et al. (2014), Raoofi (2020), and Khan et al. (2022).

Today, renewable energy sources are a conceivable option to reduce the devastating effects of the planet's rising temperature and global climate change. Renewable energy sources, especially solar and wind energy, are clean, green, and environmentally friendly. They do not emit CO2 and other GHGs into the atmosphere during consumption.

In addition to their positive environmental contributions, renewable energies help reduce energy costs by facilitating access to energy in developing countries. They reduce external dependency by diversifying resources; they ensure sustainability by meeting the energy needs of countries from local sources. Moreover, as a developing and growing sector, renewables contribute positively to employment.

Due to limited fossil fuel reserves, rapid depletion, and the privileges of renewable energy sources, renewable energy investments are expanding and innovations are being implemented at a rapid pace. In the years to come, renewable energy sources will serve as pioneers in providing the world's energy supply.

Turkey is approximately 74% dependent on foreign sources to meet its energy demand. The country's dependence on foreign sources for energy increases the importance of renewable energy sources. Turkey should, therefore, continue its efforts to increase its share of renewable energy sources in the national energy mix, as well as add nuclear energy in line with the goals of reducing foreign dependency on energy. In turn, these steps will maximize the country's use of local resources and combat climate change.

In this context, Turkey should refrain from importing energy-specific technology. Instead, the country should focus on its development of necessary technological infrastructures for the optimum use of renewable energy resources. In this respect, it would be a significant and appropriate decision for Turkey to invest in highly efficient renewable energy resources and technology.

In addition, necessary incentives should be provided to increase investments. Procedures that facilitate investments should also be implemented. These steps are essential in reducing external dependence on energy and sustainability of economic growth.

As one of the highest solar energy potentials in Europe, with an average of 2,640 hours of sunlight per year, Turkey's energy potential has not yet been fully utilized. The solar energy sector can be expanded, including added incentives and support. Turkey's wind energy potential is also high, especially in the Aegean and Marmara regions. Its rapidly growing wind energy sector should continue. The country's hydroelectric potential is also promising due to its geographical location and water resources. However, environmental impacts and sustainability issues should be taken into consideration during the planning and implementation of hydroelectric projects.

Turkey is one of the world's leading countries in GE. High geothermal activity has been seen in the western region of the country, especially in the Aegean region. The use of GE for both electricity generation and heating can increase. Turkey's agriculture and livestock sectors create significant potential for biomass and biogas energy. Converting these resources into energy can provide benefits in terms of both energy generation and waste management.

When combining all these suggestions, it is important to spotlight the role of technological development for each one. Sustainability in this field can only be achieved through a strong technological infrastructure and continuous developments.

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