SOCIOECONOMIC EVALUATION OF GEOTHERMAL ENERGY IN TÜRKİYE

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ABSTRACT

SOCIOECONOMIC EVALUATION OF GEOTHERMAL ENERGY IN TÜRKİYE

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As a domestic, reliable and non-intermittent energy resource, geothermal energy offers a clean and sustainable option for diversifying energy supply, reducing carbon emissions and strengthening energy security. Türkiye has substantial geothermal potential and became one of the world's fastest-growing geothermal power markets between 2015 and 2020. However, the recent slowdown in geothermal investments raises important questions about the drivers of sectoral development and the barriers to further expansion. To address these issues, this thesis examines geothermal development in Türkiye and its socio-economic impacts through a combination of qualitative and quantitative methods. The Technological Innovation System (TIS) analysis and semi-structured interviews reveal that institutional, financial, technological and social-environmental barriers continue to constrain sectoral development. These qualitative findings further indicate that realizing Türkiye's geothermal potential requires moving beyond electricity generation toward integrated and direct-use applications. Complementing these qualitative insights, the Social Accounting Matrix (SAM) multiplier analysis demonstrates that combining geothermal heat and power production generates greater economy-wide benefits than

electricity generation alone. Furthermore, the thesis develops an electricity-disaggregated Computable General Equilibrium (CGE) model, whose scenario results indicate that subsidies remain essential for geothermal power expansion. The findings further suggest that geothermal energy can contribute to decarbonisation and energy security by displacing fossil-fuel-based electricity generation, while direct-use applications represent a key pathway for future development. Overall, the thesis concludes that the long-term development of geothermal energy in Türkiye depends not only on expanding power capacity but also on promoting diversified geothermal utilization through policies addressing institutional, financial, technological, social and environmental challenges.

Keywords: Geothermal, opportunities and challenges, Technological Innovation System (TIS), Social Accounting Matrix (SAM) multiplier analysis, Computable General Equilibrium (CGE) model

ÖZ

TÜRKİYE'DE JEOTERMAL ENERJİNİN SOSYOEKONOMİK DEĞERLENDİRMESİ

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Yerli, güvenilir ve kesintisiz bir enerji kaynağı olan jeotermal enerji; enerji arzının çeşitlendirilmesi, karbon emisyonlarının azaltılması ve enerji güvenliğinin güçlendirilmesi açısından temiz ve sürdürülebilir bir seçenek sunmaktadır. Türkiye önemli bir jeotermal potansiyele sahip olup 2015-2020 döneminde dünyanın en hızlı büyüyen jeotermal elektrik pazarlarından biri hâline gelmiştir. Ancak son yıllarda jeotermal yatırımlarındaki yavaşlama, sektörün gelişimini şekillendiren dinamikler ile daha fazla büyümesinin önündeki engellere ilişkin önemli soruları gündeme getirmektedir. Bu tez, Türkiye'de jeotermal enerjinin gelişimini incelemek ve jeotermal enerjinin sosyoekonomik etkilerini değerlendirmek amacıyla nitel ve nicel yöntemleri bir arada kullanmaktadır. Teknolojik İnovasyon Sistemi (TİS) analizi ve yarı yapılandırılmış görüşmeler, kurumsal, finansal, teknolojik ve sosyal-çevresel engellerin sektörün gelişimini sınırlamaya devam ettiğini ortaya koymaktadır. Bulgular, Türkiye'nin jeotermal potansiyelinin tam olarak değerlendirilebilmesi için elektrik üretiminin ötesine geçilerek entegre ve doğrudan kullanım uygulamalarına önem verilmesi gerektiğini göstermektedir. Bu nitel değerlendirmeleri tamamlayan

Sosyal Hesaplar Matrisi (SHM) çarpan analizi, jeotermal ısı ve elektrik üretiminin birlikte değerlendirilmesinin yalnızca elektrik üretimine kıyasla ekonomi genelinde daha yüksek faydalar sağladığını ortaya koymaktadır. Ayrıca tez kapsamında geliştirilen, elektrik üretim teknolojilerini ayrıştıran Hesaplanabilir Genel Denge (HGD) modeli, jeotermal üretim kapasitesinin artırılmasında teşvik mekanizmalarının önemine işaret etmektedir. Sonuçlar, jeotermal enerjinin fosil yakıt kaynaklı elektrik üretiminin yerini alarak karbonsuzlaşma ve enerji güvenliğine katkı sağlayabileceğini, doğrudan kullanım uygulamalarının ise sektörün gelecekteki gelişimi açısından önemli bir fırsat sunduğunu göstermektedir. Genel olarak tez, Türkiye'de jeotermal enerjinin uzun dönemli gelişiminin yalnızca elektrik kurulu gücünün artırılmasına değil, aynı zamanda kurumsal, finansal, teknolojik, sosyal ve çevresel zorlukları birlikte ele alan politikalarla birlikte, kaynağın farklı kullanım alanlarında değerlendirilmesinin desteklenmesine bağlı olduğunu ortaya koymaktadır.

Anahtar Kelimeler: Jeotermal enerji, fırsatlar ve zorluklar, Teknolojik İnovasyon Sistemi (TİS), Sosyal Hesaplar Matrisi (SHM) çarpan analizi, Hesaplanabilir Genel Denge (HGD) modeli

To my beloved family and to those who have always believed in me

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LIST OF ABBREVIATIONS

CBRT	Central Bank of the Republic of Türkiye
CES	Constant Elasticity of Substitution
CET	Constant Elasticity of Transformation
CGE	Computable General Equilibrium
CHP	Combined Heat and Power
EGS	Enhanced Geothermal Systems
EMRA	Energy Market Regulatory Authority
GAMS	General Algebraic Modelling System
GDP	Gross Domestic Product
GeoCGE-TR	Geothermal CGE Model for Türkiye
GeoMPSGE-TR	Geothermal MPSCGE Model for Türkiye
GEOSAM	Geothermal Social Accounting Matrix
IEA	International Energy Agency
I-O	Input-Output
IRENA	International Renewable Energy Agency
JED	Geothermal Energy Association
JESDER	Geothermal Power Plant Investors Association
MAPEG	General Directorate of Mining and Petroleum Affairs
MENR	Ministry of Energy and Natural Resources
MPSGE	Mathematical Programming System for General Equilibrium
MTA	General Directorate of Mineral Research and Exploration
NEP	Türkiye National Energy Plan 2022
NGO	Non-Governmental Organization
OAZs	Organized Agricultural Zones
PV	Photovoltaics
R&D	Research and Development
RE	Renewable Energy

RSM	Risk Sharing Mechanism
SAM	Social Accounting Matrix
TEİAŞ	Turkish Electricity Transmission Corporation
TIS	Technological Innovation System
TurkStat	Turkish Statistical Institute
YEKDEM	Renewable Energy Resources Support Mechanism
YİKOB	Investment Monitoring and Coordination Directorates

CHAPTER 1

INTRODUCTION

The adoption of the Sustainable Development Goals (SDGs) and the Paris Agreement in 2015 have been the key milestones for the development of the global green transition. While SDG 7 calls for universal access to affordable, reliable and sustainable energy, the Paris Agreement seeks to limit global warming at 1.5 °C and achieve net-zero emissions by 2050. In line with these global commitments, the energy transition has emerged as a key priority on countries' agendas. Along with the scenarios of abandoning fossil fuels, countries have raced to develop new technologies that will ensure the integration of renewable energy sources into the grid and increase the flexibility of energy systems. Nonetheless, recent global developments have highlighted that renewable energy development is not merely an environmental priority, but also a strategic imperative.

Global shocks starting in the aftermath of the COVID-19 pandemic and deepening following the outbreak of the Russia-Ukraine war in February 2022 have demonstrated that heavy reliance on imported sources in the energy mix can threaten both energy security and electricity price stability (Robinson, 2022; Bolton, 2026). Indeed, disruptions to Russian gas supplies to Europe propelled electricity prices to unprecedented levels, imposing significant costs on consumers and the broader economy. Similarly, the recent conflict between the US, Israel and Iran, which led to significant disruptions in oil and gas supplies due to the closure of the Strait of Hormuz, has once again highlighted the vulnerability of countries reliant on imported energy to geopolitical risks (Zackriat, 2026). Indeed, these developments demonstrate the critical importance of accelerating renewable energy development, not only to achieve emission reduction targets but also to strengthen energy security, enhance energy independence and improve economic resilience in the face of global

uncertainties (IRENA, 2026; SHURA, 2026). To address these unprecedented supply shocks, geothermal energy, characterized by its domestic availability and reliability, emerges as a particularly promising alternative, especially when compared to imported fossil fuels and intermittent renewable sources. In response to energy security concerns arising from recent energy crises, many countries have already begun to provide stronger policy support for geothermal (IEA, 2024).

Unlike other renewable energy sources, geothermal energy can provide a stable energy supply and enable continuous electricity generation regardless of weather conditions or seasonal variations (Kubota et al., 2013). With a capacity factor of up to 96%, geothermal energy outperforms other renewable technologies (Lund, 2003) and emits less than coal and natural gas, highlighting its potential in the transition to future low-carbon energy systems. On the other hand, through its flexible operation, it can enhance grid stability alongside energy storage technologies and play a key role in enabling the integration of variable renewable energy sources such as wind and solar into the grid (IEA, 2024). Furthermore, geothermal does not require significant grid or infrastructure investment when used for decentralized low-heat consumption in homes or commercial buildings compared with that required for gas and oil (Nkinyam et al., 2025). It has also a less ecological effect as a source requiring less land (Li et al., 2015).

Today, the potential of geothermal energy to support the energy transition is gaining growing recognition governments worldwide (Spijkerboer et al., 2022) and many countries have started to set geothermal-specific targets in their national energy plans (IRENA & IGA, 2023). The United States aims to increase its installed geothermal power generation capacity to 60 GWe under GeoVision 2019 while enhancing its Enhanced Geothermal Systems (EGS) and geothermal heating/cooling potential. China, through its “13th Five-Year Plan for Geothermal Energy Development and Utilization” adopted in 2017, focuses on accelerating geothermal heating and cooling applications. The International Energy Agency and French Environment and Energy Management Agency have declared geothermal energy “*the most cost-effective solution for heating*”. In Africa, Kenya has set ambitious targets to double its geothermal power capacity to 1.6 GWe by 2030. On the other hand, Dominica has

positioned geothermal energy as the main driver of its energy transition, targeting 100 % renewable generation by 2030. As a resource-rich country, Türkiye has also positioned itself among the countries aiming to harness its geothermal potential.

Türkiye, with a population exceeding 85 million, ranked as the world's 17th-largest economy in 2024 (World Bank Group, 2025). The country has also recorded the fastest growth in energy demand among the OECD countries over the past two decades (Bulut et al., 2025). In line with rising electricity demand, installed power capacity expanded substantially over the last decade, driven primarily by renewables, from 69 GW in 2014 to 116 GW in 2024 (TEİAŞ, 2025). As a significant development, Türkiye ratified the Paris Agreement in 2021 and updated its Nationally Determined Contribution (NDC) in 2023, committing to a 41% reduction in greenhouse gas emissions by 2030 compared to a business-as-usual scenario and reaffirming its net-zero target for 2053 (OECD, 2025).

As a part of the Paris Agreement since 2021, Türkiye has prioritized long-term strategy and action plans to accelerate emissions mitigation. Indeed, the country has adopted two key energy-policy goals: maximizing the use of domestic energy sources and ensuring a reliable, affordable and environmentally sustainable energy supply (Lise & Uyar, 2022). At this point, the energy sector, which accounted for the largest share of national CO_2 emissions in 2022, requires special attention, as 86.6% of emissions originate from this sector, including 32.6% from electricity and heat generation (TurkStat, 2024a). Having a clean and sustainable energy strategy to increase the percentage of domestic and renewable energy in electricity production, Türkiye generated 42% of its electricity from renewable energy sources in 2022 and its renewable capacity constituted 54% of its total installed capacity (EMRA, 2023a). Nonetheless, the climate-dependent variability of renewables necessitates continued reliance on imported fossil fuels, undermining Türkiye's efforts to enhance energy security and achieve its long-term energy transition goals. Despite significant growth in the country's renewable energy capacity, fossil fuels still constitute a significant portion of electricity generation, accounting for 22% from natural gas and 34% from coal in 2022 (EMRA, 2023a). In the same year, Türkiye imported the 99% of its natural gas (EMRA, 2023b) and 61% of its coal supply (IEA, 2023), leaving the

country highly exposed to price volatility and geopolitical risks. Indeed, driven by the peak in international energy prices in 2022 due to Russia-Ukraine war, Türkiye's energy import bill reached USD 96,548 million in December 2022 (CBRT, 2023).

In the National Energy Plan (2022-2035) of Türkiye published in 2022, it has been declared that the share of wind and solar energy in electricity generation, which was 11.7% in 2020, will gradually increase to 34.3% by 2035 while decreasing the share of fossil fuels, commissioning of nuclear plants and accelerating investments in storage technologies. All these long-term strategy plans suggest that Türkiye will not entirely phase out its fossil plants in the medium term and will continue to rely on intermittent energy sources in its power generation, which underscores the importance of geothermal in supporting the country's low-carbon electricity system transition as a domestic, non-intermittent and environmentally friendly energy source.

Beyond electricity generation, its integrated use for electricity and heat production may contribute to reducing dependence on imported fossil fuels while supporting economic growth, energy security and environmental sustainability. Furthermore, it has the potential to generate broader economy-wide benefits through stronger inter-sectoral linkages, higher value added and increased employment opportunities.

From a historical perspective, Türkiye's operational geothermal installed capacity has increased dramatically over the past two decades, rising from just 14.8 MWe in 2003 to 1,691 MWe in 2023. This rapid expansion has also created additional opportunities for the direct utilization of geothermal resources. However, despite this remarkable growth in installed capacity, particularly after 2010, geothermal power investments have exhibited a declining trend in recent years, raising several important research questions that this thesis seeks to address:

1. What factors have driven geothermal energy expansion in Türkiye and what barriers continue to constrain its further development?
2. What are the key opportunities and challenges shaping the development of geothermal energy in Türkiye?

3. What are the economy-wide impacts of integrated geothermal energy use, including electricity and heat generation, relative to alternative electricity generation technologies?
4. How do different geothermal subsidy scenarios influence the further expansion of geothermal power capacity in Türkiye?

To better understand the key drivers of geothermal expansion and the factors constraining its further growth, it is essential to examine the evolution of geothermal energy in Türkiye from both historical and institutional perspectives, while also identifying the opportunities and challenges facing the sector. Furthermore, assessing the impacts of different geothermal expansion scenarios through comparative analyses is crucial for revealing its broader potential. Accordingly, this thesis aims to evaluate geothermal energy development in Türkiye and its socioeconomic impacts using a mixed-methods approach, combining qualitative and quantitative techniques to provide a comprehensive and multi-dimensional analysis. Throughout the thesis, the qualitative findings inform the quantitative analyses, while the quantitative results provide economy-wide evidence that complements and contextualizes the qualitative insights. Together, these approaches integrate macro-level socioeconomic analysis with micro-level institutional and stakeholder perspectives, enabling the triangulation of findings and a more robust assessment.

In addition to introducing the historical development of geothermal energy in Türkiye, this thesis examines the expansion of the geothermal sector through the Technological Innovation System (TIS) framework, focusing on its structural components, system functions and their interactions. As an initial assessment of the drivers and barriers shaping the diffusion of geothermal energy in Türkiye, it provides valuable insights into the institutional, technological, financial and policy-related factors influencing the sector's evolution. Furthermore, as the first comprehensive TIS-based assessment of geothermal energy development in Türkiye, this study contributes to the limited TIS literature on geothermal energy by providing evidence from a geothermal-rich country.

The Turkish Geothermal TIS is analysed using official documents, reports and market data. While these sources provide valuable insights into sectoral

development, they offer only a limited understanding of stakeholders' perspectives and experiences. To complement the TIS analysis, this study also employs semi-structured interviews with key stakeholders in the Turkish geothermal sector. Although semi-structured interviews are widely used in the geothermal energy literature, systematic qualitative assessments of stakeholder perspectives remain limited in the Turkish context. Accordingly, this study provides the first comprehensive qualitative assessment of geothermal development in Türkiye, an important case study given its position as Europe's leader and the world's fourth-largest in installed geothermal power capacity.

As frequently emphasized during the interviews, geothermal energy can provide significant economic and social benefits to resource-rich countries. Although many policy documents and the literature emphasize the dual role of geothermal energy in electricity and heat production, this key role remains insufficiently demonstrated within a systematic analytical framework. Therefore, providing clear and quantifiable evidence of these benefits is essential for supporting geothermal deployment and guiding evidence-based policymaking.

Drawing on this perspective, this thesis aims to quantitatively assess the socioeconomic impacts of geothermal energy development through a comparative approach. By incorporating the economic dimension of geothermal energy into a Social Accounting Matrix (SAM) multiplier analysis, it contributes to the Turkish geothermal literature, which has been predominantly shaped by geological and technical research. Given the limited number of geothermal-focused SAM studies across countries, the evidence from the Turkish case offers a valuable contribution to the SAM literature. Moreover, the detailed disaggregation of the electricity sector, specifically the separation of geothermal electricity and geothermal heat generation, constitutes a novel methodological extension in electricity-based SAM development. To the best of our knowledge, this is the first study to explicitly incorporate geothermal heat generation into a SAM multiplier framework. The SAM constructed within the scope of this thesis, based on the most recent 2023 I-O table, also provides an up-to-date dataset for future energy-based Computable General Equilibrium (CGE) applications on Türkiye.

Building on the SAM multiplier analysis, which highlights the importance of modelling geothermal energy alongside electricity and heat generation, this thesis develops a comprehensive Geothermal MPSGE Model for Türkiye (GeoMPSGE-TR) with a highly disaggregated electricity sector and a detailed representation of geothermal energy. Despite the growing CGE literature on renewable energy, geothermal energy has received relatively limited attention. In the case of Türkiye, geothermal energy is rarely represented as a distinct electricity generation technology in CGE models and, to the best of our knowledge, no study has evaluated dedicated geothermal policy scenarios. Accordingly, this thesis represents the first attempt to examine geothermal policy scenarios within a CGE framework for Türkiye while explicitly incorporating the heating dimension into the geothermal CGE literature. Given that stakeholders interviewed largely attributed the expansion of geothermal installed capacity in Türkiye to incentive mechanisms, the scenario analysis of this study provides policy-relevant insights into the role of subsidies in supporting further geothermal capacity expansion and achieving the country's long-term geothermal development targets.

The rest of the thesis is organized as follows. Chapter 2 provides an overview of the global and national geothermal energy outlook. Chapter 3 presents the TIS framework for analysing the diffusion of geothermal energy in Türkiye, while Chapter 4 discusses the opportunities and challenges for geothermal energy in Türkiye identified through stakeholder interviews. Chapter 5 develops a SAM for the Turkish geothermal energy sector and conducts scenario analyses incorporating geothermal heating. Chapter 6 presents the development of the GeoMPSGE-TR model and examines the results of geothermal subsidy scenarios. Finally, Chapter 7 concludes the thesis by summarizing the main findings, discussing the key policy implications and outlining the limitations of the study and directions for future research.

CHAPTER 2

GEOTHERMAL ENERGY: GLOBAL STATUS AND TÜRKİYE

Following an introduction to geothermal energy and its various applications, this chapter explores the global outlook of geothermal energy as well as its development in Türkiye, with a particular focus on its current status and future potential.

2.1. Geothermal Energy

Derived from the Greek words geo (“earth”) and thermal (“heat”), geothermal energy refers to the heat or energy produced from the Earth (Nasruddin et al., 2016). This heat, originating from Earth’s molten interior and the radioactive decay of elements within deep rock formations (Avci et. al, 2020) and stored beneath the Earth’s surface over millions of years, provides the primary source of geothermal energy. Indeed, the temperature difference between the Earth’s core and its surface generates a geothermal gradient through which thermal energy flows upward to the surface in the form of steam or hot water. In this way, geothermal resources located in areas with high heat flow to the surface can be efficiently extracted and harnessed for electricity generation as well as direct use and heat pump applications (Archer, 2020).

Although the locations of geothermal energy sources vary due to geological and geophysical characteristics, they are unevenly distributed and primarily concentrated in three key regions worldwide. Among these regions, the first zone is the west coast of the circum-Pacific belt, which includes Australia, western Indonesia, the Philippines, Japan, China and Taiwan. The second zone is the Mid-Atlantic Ridge, stretching from the northern end of Iceland and extending mostly beneath the ocean. The third zone is the Mediterranean-Himalayan region, encompassing areas such as Italy and Tibet in China (Sharmin et al., 2023).

As outlined by Nkinyam et al. (2025), geothermal energy systems and sources are classified in several ways. Despite the lack of strict standardization, high-temperature systems can be characterized by reservoir temperatures above 150 °C, whereas medium- and low-temperature systems fall within the ranges of 100-150 °C and 30-100 °C, respectively. Reservoirs with temperatures below 30 °C are classified as extremely low-temperature systems. In addition to temperature-based distinctions, geothermal resources can also be categorized according to their origin, including hydrothermal, hot dry rock, magma and geo-pressured resources. Among these resources, hydrothermal systems, also referred to as conventional geothermal systems, are limited to specific geological settings such as volcanic regions, subduction zones and deep continental rifts; in contrast, hot dry rock or Enhanced Geothermal Systems (EGS), as emerging technologies, can be implemented anywhere on Earth by tapping into the heat stored in granitic formations (Baba & Chandrasekharam, 2022). While hydrothermal systems require rocks with high permeability and the presence of groundwater to extract heat (Sharmin et al., 2023), the EGS enable the extraction of heat from rocks that are not naturally fractured and generally exhibit low permeability by injecting water into them (Gallup, 2009). Therefore, the development of EGS as next-generation geothermal technologies can reduce the dependence on location-specific hydrothermal resources and enable heat extraction from greater depths, even in regions lacking pre-existing hydrothermal reservoirs (IEA, 2024).

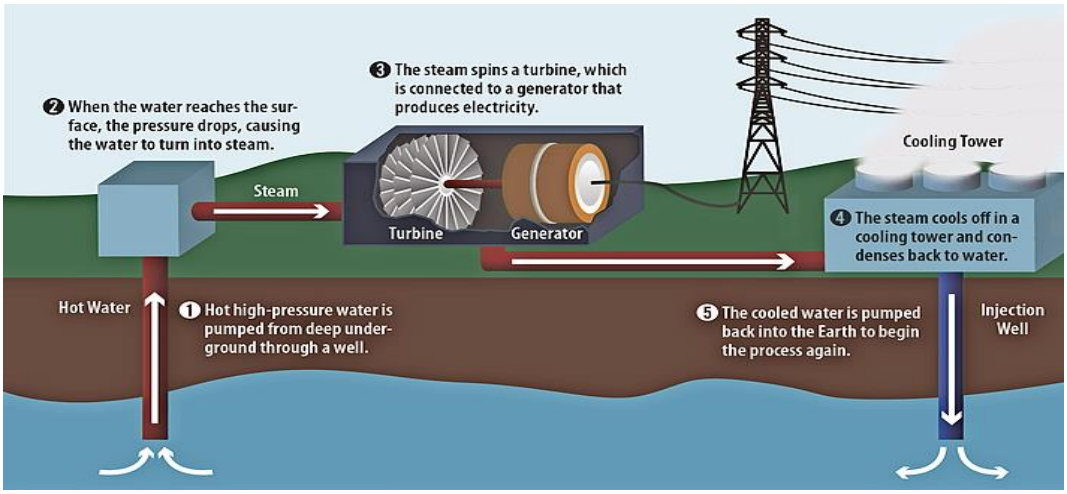

Figure 2.1. Operation of a geothermal hydrothermal system

Source: Igwe (2021)

Figure 2.1 illustrates the main stages of geothermal electricity generation in a hydrothermal system, from extracting hot, high-pressure geothermal fluid to reinjecting the cooled water into the Earth via injection wells. Fundamentally, geothermal power plants use heat from underground fluids to produce steam that powers turbines to generate electricity, employing three main technologies: dry steam, flash steam and binary cycle systems. Indeed, this technology choice depends on geothermal resource conditions, such as reservoir temperature and pressure, reservoir properties, fluid chemistry and whether the geothermal fluid is in the vapour or liquid phase (IEA, 2024). While dry steam and flash steam technologies exploit vapour-dominated and liquid-dominated hydrothermal reservoirs, respectively, binary plants are used for reservoir water temperatures below 150 °C. In these systems, a secondary fluid with a low boiling point circulates in a closed cycle instead of the geothermal fluid itself, absorbing geothermal heat via a heat exchanger for power generation (Melikoglu, 2017). Among the three technologies, dry steam systems are regarded as the simplest and most efficient, whereas flash steam plants are the most widely used worldwide and binary systems continue to expand geothermal deployment opportunities (Hsieh & Liu, 2025).

Today, integrating geothermal energy into the electricity mix provides countries with numerous advantages, including continuous and predictable power generation, operational flexibility, clean and sustainable energy production, enhanced energy security and significant reductions in CO_2 emissions (Pan et al., 2019). On the other hand, uninterrupted electricity production depends on the sustainability of geothermal reservoirs. Geothermal energy is often classified as a renewable resource; however, its long-term sustainability relies on effective reservoir management. At this point, proper reinjection practices are particularly important for maintaining reservoir pressure and temperature (Haklıdır, 2020).

2.2. Direct Utilization of Geothermal Energy

Depending primarily on the temperature of the fluid and its chemical characteristics, geothermal energy offers a broad range of applications, as illustrated in Figure 2.2.

While medium- to high-temperature geothermal resources are primarily used for power generation, low- to medium-temperature resources are widely applied in various direct-use applications, including space heating and cooling, bathing and recreation, as well as diverse agricultural and industrial processes (ESMAP, 2022). Ground-source heat pumps enable low-temperature heat transfer to and from the near-surface at depths of less than 100 m, providing the low- and medium-temperature heating and cooling end uses (IEA, 2024).

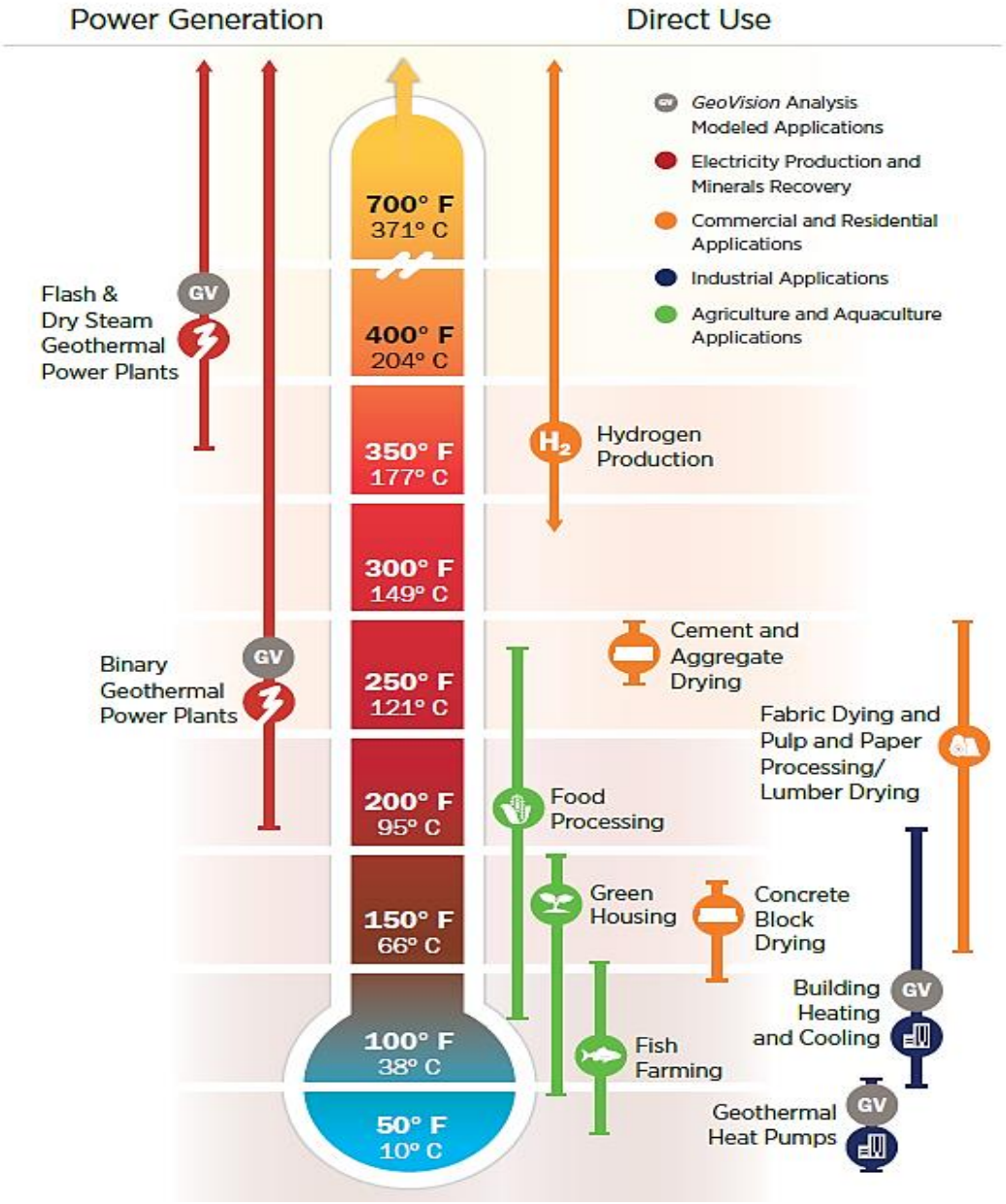

Figure 2.2. Different uses of geothermal energy

Source: GeoVision (2019)

As illustrated in Figure 2.3, cascaded (integrated) geothermal systems enable the sequential utilization of geothermal fluid. After electricity generation, the remaining thermal energy in the fluid can be used for additional applications such as heat pumps, greenhouse heating, food and agricultural drying and aquaculture (Anderson & Rezaie, 2019). Thus, energy derived from a single geothermal resource is used in a cascading manner across multiple sectors, maximizing resource efficiency.

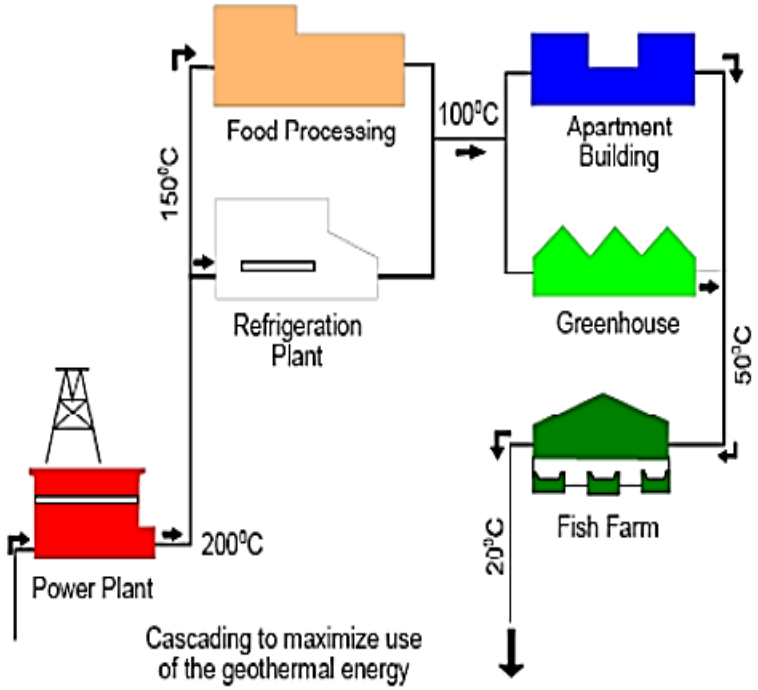

Figure 2.3. An example of geothermal cascaded (integrated) system

Source: Lund (2010)

Besides supplying heat and electricity, geothermal fluid can provide plant operators with commercially valuable by-products such as silica, lithium, manganese, zinc and sulphur (Bakane, 2013). Geothermal energy also serves as an important element of hybrid thermo-electric generation systems, where it is combined with solar and fossil energy sources, as well as with process-heat applications such as CO_2 capture and thermal desalination (Wendt et al., 2018). Indeed, when hybridized with other renewable sources, geothermal energy can provide significant advantages, including enhanced energy efficiency, greater system reliability, improved capacity factors, grid stabilization, reduced transmission infrastructure costs and optimized land use (Renewable Central, 2025). Furthermore, geothermal energy is expected to play a

critical role in future green hydrogen production, as demonstrated by recently initiated projects, including a commercial project in Iceland and a pilot project in New Zealand (IRENA & IGA, 2023).

2.3. Geothermal Energy Worldwide

Among renewable energy sources, geothermal energy stands out for its long history of use, predating the development of solar, wind and biopower technologies by centuries. Indeed, geothermal energy has been used since prehistoric times for various purposes, including heating, bathing, cooking and agricultural applications. To illustrate, the first district heating system was built in the central French town of Chaudes-Aigues in the 14th century and many other modern examples have since followed it, providing heat for domestic, industrial and commercial buildings (Johnston et al., 2011).

In terms of electricity generation, the first pilot geothermal power plant was commissioned in Larderello, Italy in 1904 and the first commercial one (0.3 MW) in 1913. Thereafter, Italy remained the sole producer of geothermal energy until 1958, when another geothermal plant began operation in New Zealand (Ediger & Akar, 2023). Particularly after the Second World War, geothermal energy attracted the attention of many countries as a locally available and economically competitive energy source (Dickson & Fanelli, 2013). Beginning in the 1960s and accelerating after the 1973 oil crisis, the number of countries investing in geothermal energy grew significantly throughout the 1970s and 1980s (Kose, 2007). However, the share of geothermal energy in the global energy mix has remained limited, both compared with conventional fossil fuels and major renewables such as hydropower, wind and solar (Axelsson, 2024). Indeed, geothermal energy accounted for only 0.4% of global renewable installed capacity and 1.1% of renewable electricity generation in 2023 (IRENA, 2025a). Despite this contribution within renewables, its role in the overall power mix is even more modest, with geothermal electricity representing only about 0.3% of total global electricity generation (Kirkil et al., 2026). Nevertheless, there are some countries, in which geothermal constitutes a significant element of the energy matrix, contributing not only to their electricity generation but also to a range of direct use applications.

In 2023, geothermal electricity constituted roughly 20% of total geothermal final energy consumption (IEA, 2024). Over the past decade, global geothermal installed capacity increased by almost 40% and exceeded 15,000 MW in 2023. Türkiye, Indonesia and Kenya accounted for more than three-quarters of all new capacity additions during this period (IEA, 2024). As illustrated in Figure 2.4, the combined capacity of the top 10 countries with the highest geothermal installed capacity in 2023 reached 13,985 MW. The United States, Indonesia, the Philippines, Türkiye and New Zealand emerge as the leading countries, even surpassing pioneer Italy. In addition to these countries, often referred to as the "1 GWe club" with their geothermal plants operating for decades, new countries have entered the field of geothermal development in recent years, such as Belgium, Chile, Colombia, Croatia, Honduras and Hungary (IRENA & IGA, 2023).

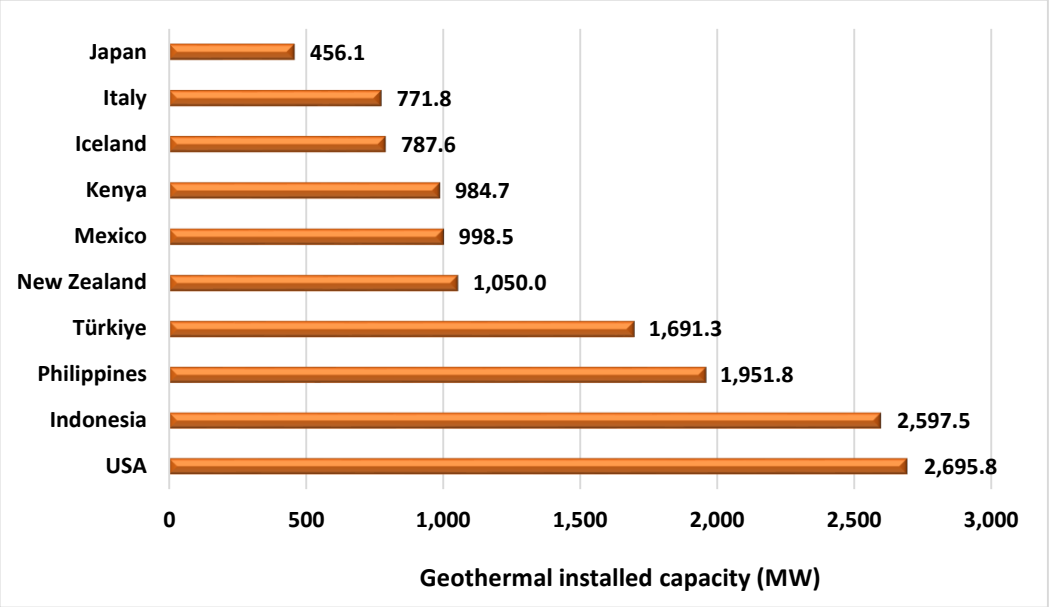

Figure 2.4. The top 10 countries with the highest geothermal installed capacity in 2023

Source: IRENA (2025a)

Although installed capacity can serve as an important indicator of geothermal development across countries, there are also some countries where geothermal energy contributes more than 10% to electricity generation despite their relatively small geothermal installed capacities, such as Kenya (45%), Iceland (over 30%), El Salvador (25%) and New Zealand, Nicaragua, Costa Rica and the Philippines (10%-20%) (Gutiérrez-Negrín, 2024).

Beyond electricity generation, the direct utilization of geothermal energy has also evolved over time, with a different set of leading countries as illustrated in Figure 2.5. Based on the 2020 figures, China (40.6 GWth), the United States (20.7 GWth), Sweden (6.7 GWth), Germany (4.8 GWth) and Türkiye (3.5 GWth) are the global leaders with their geothermal direct-use capacity, including heat pumps (Lund & Toth, 2021). As of 2020, the worldwide installed capacity for geothermal heating and cooling reached 107.4 GWth, with geothermal heat pumps accounting for 72% of this capacity, while the remaining 28% comprised direct-use geothermal heating and cooling systems (Celikbilek & Sen, 2025). Besides geothermal heat pumps, geothermal energy is also widely used in other heating and cooling applications, for example, district heating in China, Iceland and Türkiye; hot spring resorts in Japan; and bathing facilities in Türkiye (IRENA & IGA, 2023).

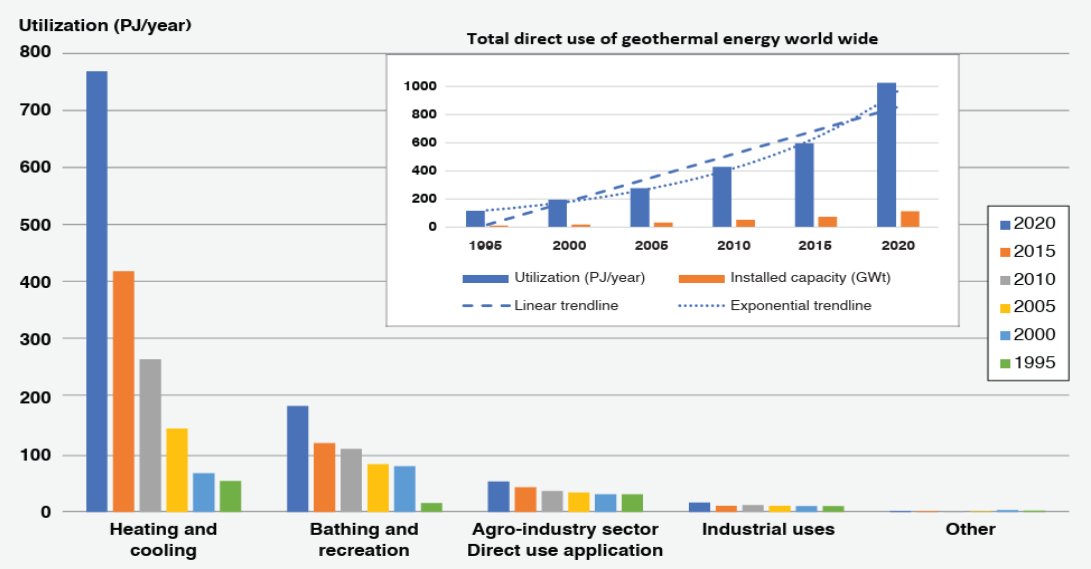

Figure 2.5. The development of geothermal direct utilization applications, 1995-2020

Source: ESMAP (2022)

A variety of financial and economic incentives are employed worldwide to support geothermal projects, such as tax breaks and direct subsidies (USA), feed-in tariffs (Japan, Kenya, Türkiye), research and innovation funding, grants and loans, risk-mitigation and insurance schemes (France, Germany, Iceland, the Netherlands, Switzerland, Türkiye, Hungary) and carbon-revenue mechanisms (IRENA & IGA, 2023). Although conventional geothermal systems currently account for less than 1%

of global energy demand, continued technological innovation, cost reductions and supportive policy incentives could enable next-generation geothermal systems to expand, thereby supplying up to 15% of global electricity demand growth by 2050 (IEA, 2024). This highlights the potentially pivotal role of geothermal energy in future electricity systems.

2.4. Development of Geothermal Energy in Türkiye

Türkiye's location along the Alpine-Himalayan orogenic belt, characterized by young faults and active volcanism, underpins its significant geothermal energy potential (Kaya, 2012). While geothermal resources are spread over many parts of the country, as illustrated in Figure 2.6, those for power generation exist in the Büyük Menderes and Gediz Grabens, in Western Anatolia, where the exploration and drilling activities were mainly concentrated. Indeed, 78% of potential areas are in Western Anatolia, 9% in Central Anatolia, 7% in the Marmara Region, 5% in Eastern Anatolia and 1% in other regions (Simsek et al., 2005). In addition to favourable geological conditions, higher population density, increasing electricity demand and industrial activity contributed to the intensification of geothermal exploration activities mainly in the western part of the country (Pedrosa et al., 2026).

According to the General Directorate of Mineral Research and Exploration of Türkiye (MTA), 90% of geothermal resources in the country are with low (below 90 ℃) to medium (90-150 ℃) enthalpy, suitable for direct utilization applications such as district heating, thermal tourism, various industrial applications, while only 10% with high enthalpy (exceeding 150 ℃) is for electricity generation. The maximum recorded geothermal well-bottom temperature to date is 341 °C, measured in a well drilled in Niğde (Şener et al., 2023). Over 1,000 wells have been drilled specifically for geothermal power generation, with some in Western Anatolia reaching depths of up to 4,500 meters (Tut Haklidir & Nyokabi, 2020). The total proven geothermal thermal potential has reached 40,000 MWt, of which approximately 15% is utilized for direct heat applications and about 4% for electricity generation (MENR, 2024a). However, geological evidence suggests that Türkiye's geothermal potential is substantially higher, including yet-undiscovered resources (Bulut et al., 2025).

Indeed, the country's total theoretical geothermal energy capacity is estimated at 62,000 MWt (Şener et al., 2023).

Geothermal research and exploration in Türkiye have been carried out since the 1960s and accelerated mainly after the 1970s. Following a pilot power plant with a capacity of 0.5 MWe constructed in the Denizli-Kızıldere geothermal field in 1974, a plant with a 17.4 MWe was commissioned at the exact location in 1984 (Akpınar et al., 2008; Serpen & DiPippo, 2022) as Europe's second biggest geothermal power plant after Italy. Due to some operational challenges, the plant operated at only 5-10 MWe capacity until 2000 (Pamukcu et al., 2024).

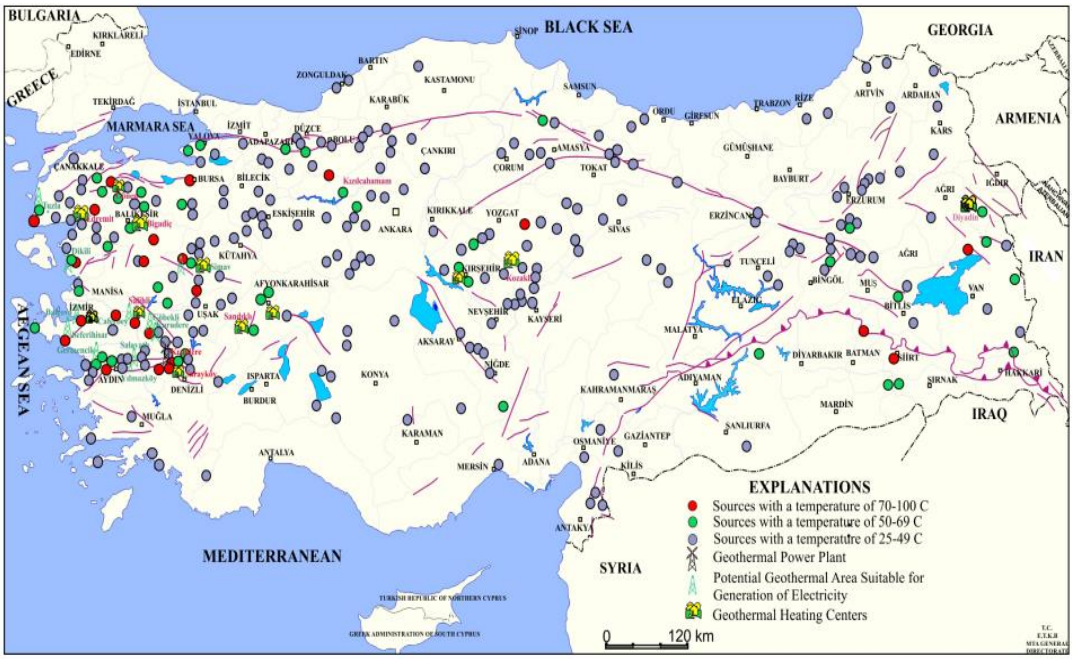

Figure 2.6. Geographical distribution of geothermal sources in Türkiye

Source: Görür and Önder (2023)

After the commissioning of the Kızıldere plant, geothermal power generation activities in the country progressed very slowly for over 20 years (Tut Haklidir, 2015). Before the 2000s, geothermal energy remained relatively underdeveloped, with limited exploration activity and low awareness of its potential (Pedrosa et al., 2026). Furthermore, due to the privatization-oriented policies adopted in the 1980s and the limited role assigned to public investment, high-enthalpy geothermal fields remained largely underutilized for a long time (Durak, 2025). Nonetheless, following

the liberalization of the Turkish energy sector in the early 2000s, the privatization of geothermal sites and the issuance of drilling licenses gained momentum (Spijkerboer & Turhan, 2025). Following these promising developments, the commissioning of Dora-I as the first private-sector geothermal power plant in 2006 was followed by the transfer of the Kızıldere plant's operating rights to Zorlu Energy under a 30-year agreement in 2008 (Kirkil et al., 2026). However, the adoption of the Law on Geothermal Resources and Natural Mineral Waters (No. 5686) in 2007, setting the rules for the exploration and exploitation of geothermal resources and the amendment in 2010 to the Renewable Energy Law, offering a feed-in tariff as Renewable Energy Resources Support Mechanism (YEKDEM) for electricity generation, were undoubtedly two critical milestones for the geothermal energy sector. YEKDEM provided the geothermal investors a guaranteed purchasing price for the electricity they generated, such as 105 USD/MWh for ten years from the commissioning date[1]. Additional incentives were also introduced to the plants for their locally produced equipment. Following these developments, geothermal energy investments for power generation increased significantly, along with growing interest from the private sector.

Other than YEKDEM, as a feed-in tariff supporting geothermal power generation, the Risk Sharing Mechanism (RSM) as a component of the "*Geothermal Development Project"* was launched in Türkiye in 2018 following the agreements signed between the World Bank (International Bank for Reconstruction and Development-IBRD) and the Development and Investment Bank of Türkiye in 2016. This project had two main components: a loan facility for resource development and the RSM. Considering the regional differences and geological risks in the exploration phases, the RSM aimed to cover 40% to 60% of the cost of failed wells and facilitate exploratory drilling activities in new areas (TÜBA, 2020) as an early-stage risk-mitigating scheme for investors. Indeed, the primary objective of the RSM was to promote geothermal exploration, especially in phases characterized by high costs and risks of failure, while uncovering the geothermal energy potential in the unexplored regions of Türkiye (Saltuk et al., 2023). In addition to power generation, with the

[1] At that time, YEKDEM set the ten-year tariff at 73 USD/MWh for hydro and wind, and 133 USD/MWh for biomass and solar.

four rounds completed so far, the RSM supported medium- and small-scale projects to encourage private investment in geothermal heating applications, particularly within greenhouse-organized agricultural zones (Yıldız et al., 2025). Furthermore, these international financial institutions have supported Türkiye's geothermal energy development not only by providing funding, but also by strengthening local expertise through technical assistance and capacity-building, while incentivizing improvements in policy and regulatory frameworks for the Turkish geothermal sector (Pedrosa et al., 2026).

2.4.1. Geothermal Energy in Policy Documents and Institutional Framework

Beyond government policies and risk-mitigation mechanisms, Turkish energy strategy papers have frequently emphasized a commitment to further geothermal development. Among recent policy documents, in the Eleventh Development Plan (2019-2023) of the country, there is the goal of "*Consistent with the target of reducing foreign dependency on energy production, exploration activities aiming at identifying the potential of domestic resources, such as lignite and geothermal, will be increased to the maximum extent*." Similarly, in the National Energy Plan 2022, the target is that "*The installed capacity of geothermal and biomass power plants will reach 5.1 GW in total by 2035*."

Other than electricity generation, the National Energy Efficiency Action Plan (2017-2023), highlights the promotion of geothermal potential in district heating systems and encourages the use of geothermal also in agricultural production processes along with other renewables. Similarly, the Twelfth Development Plan (2024-2028) outlines targets for the direct use of geothermal energy, including increasing the number of geothermal greenhouse-organized agricultural zones, promoting the adoption of regional heating and cooling systems and heat pumps and expanding geothermal heating applications.

Under Law No. 5686, investors holding geothermal fluid operation licenses suitable for integrated use are required to prioritize the use of surplus geothermal fluid for agricultural heating. Furthermore, the *Utilization of Renewable Energy Resources for*

the Purpose of Generating Electricity Law (Law No. 5346) obliges local authorities in regions with sufficient geothermal resources to meet the heating needs of settlements primarily through geothermal and solar thermal resources. As a recent development, pursuant to the 2024 amendment to the *Regulation on Increasing Efficiency in the Use of Energy Resources and Energy*, geothermal power plants with an installed capacity of 20 megawatts or more are required to ensure that waste heat is not discharged but instead utilized in alternative applications. Accordingly, such facilities are required to carry out an energy audit, either through a company authorized by the Ministry of Energy or by their own certified personnel and to submit the resulting report to the Ministry. Indeed, this new policy reaffirms Türkiye's commitment to expanding the integrated use of geothermal energy through the utilization of waste heat.

Considering the institutional framework governing geothermal energy in Türkiye, according to Law No. 5686, all geothermal resources and natural mineral waters fall under the full authority and ownership of the state. Any activity concerning these resources requires the prior issuance of a license under the provisions of this Law. Thus, in Türkiye, approval and permitting processes for geothermal energy are managed by multiple institutions, although the Ministry of Energy and Natural Resources (MENR) remains responsible for setting geothermal energy policies and overall coordination.

Applications for geothermal resource exploration licenses are submitted to the Provincial Special Administration in metropolitan municipalities and Investment Monitoring and Coordination Directorates (YİKOB) in non-metropolitan ones. The General Directorate of Mining and Petroleum Affairs (MAPEG), an affiliated institution of the MENR, evaluates whether the applicant is eligible to obtain the license. Upon a positive evaluation of MAPEG, the Provincial Special Administration or YİKOB issues the license and become responsible for local monitoring and inspection activities of licensed geothermal areas. Along with a three-year exploration license, private companies can conduct geothermal resource exploration activities in a specific geographical area, issued by MAPEG. As a public entity, MTA also provides the appropriate fields to investors through tenders while continuing its geothermal exploration, development and drilling activities.

For geothermal projects, the Environmental Impact Assessment (EIA) process begins at the early planning stage, before any licensing or operational activities are permitted. EIA reports for projects that exceed a specified generation capacity and may have adverse environmental impacts must be submitted by investors to the Ministry of Environment, Urbanization and Climate Change after obtaining the operation license. Based on the Ministry's assessment, the project may either proceed or be cancelled.

Following successful exploration activities, the thirty-year operating license entitles the holder, subject to approval by the relevant authorities and favourable opinion of MTA, to utilize geothermal water, gas and steam for electricity generation, heating, or other industrial purposes. For electricity generation, EMRA reviews pre-license applications and grants a generation license if the applicant meets the required criteria. EMRA also reviews and processes applications submitted by power plant operators seeking to benefit from the YEKDEM mechanism. On the other hand, geothermal heat generation is regulated through operating licenses granted by the relevant Provincial Special Administration or YİKOB. In the Turkish case, municipalities play an important role in the development and operation of geothermal district heating systems as a local public service. Depending on the intended use of the resource and the location of the licensed area, as well as environmental, health, agricultural and tourism-related considerations, geothermal projects may be subject to additional approvals and permits from other relevant authorities.

2.4.2. Geothermal Electricity Generation in Türkiye

After commissioning the first geothermal plant in 1984, the installed power capacity in Türkiye has expanded rapidly over time. As the first in Europe and the fourth globally today, following the US, Indonesia and the Philippines, it has a vast potential for geothermal energy. In 2020, Türkiye was the country with the highest capacity increase since 2015 and its installed capacity was projected to reach 2,600 MWe by 2025 (Huttrer, 2021).

In 2023, geothermal energy accounted for 2% of the country's total installed capacity and 3% of its electricity generation. While the share of geothermal energy may

appear modest, it demonstrates a distinct comparative advantage when its electricity generation performance is compared with that of solar and wind energy. Based on EMRA (2024), wind and solar energy constituted 11% and 13% of the total installed capacity in 2023, yet generated only 10% and 6% of Türkiye's total electricity, respectively. These figures indicate that geothermal energy outperforms other renewable sources in terms of electricity generation relative to their installed capacity.

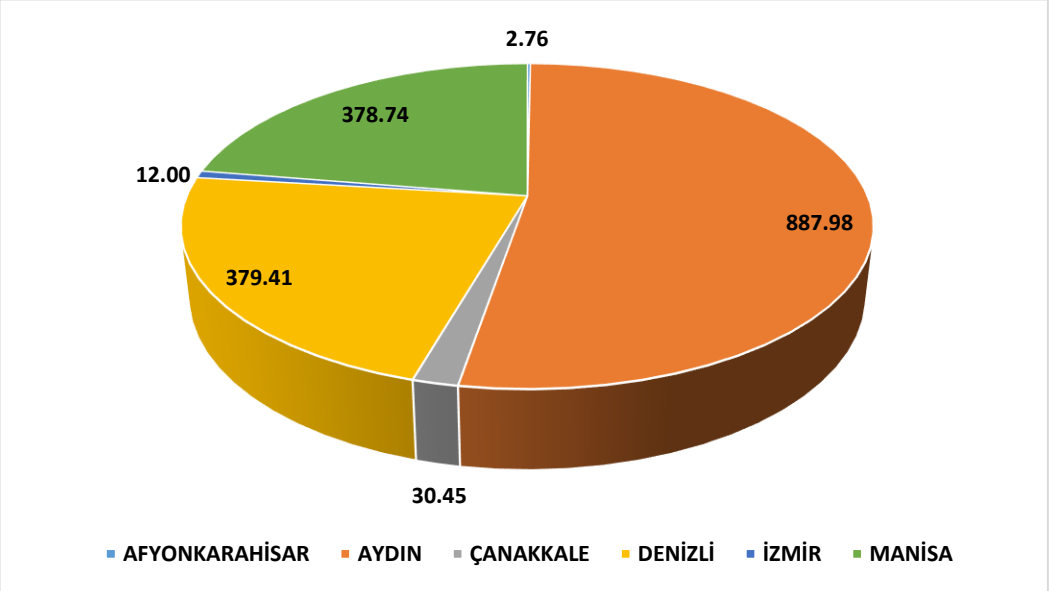

Figure 2.7. Distribution of geothermal operational installed capacity in 2023 (MWe)

Source: Author's illustration based on EMRA electricity market generation license data

The geothermal electricity sector in Türkiye has experienced remarkable growth over the past two decades. As of 2024, there are 67 licenses for geothermal electricity generation and the total operational installed capacity reached 1,691 MWe, which was 14.8 MWe in 2003. The 2030 target is to reach an installed capacity of 4,000 MWe (Lise & Uyar, 2022), given that the country's geothermal potential is estimated at approximately 4,500 MWe (Mertoglu et al., 2021).

As illustrated in Figure 2.7, geothermal installed capacity in Türkiye is concentrated in a limited number of provinces, particularly Aydın, Denizli and Manisa. In 2023, Aydın accounted for 53% of the total installed geothermal capacity with 887.98 MWe, whereas Denizli and Manisa, each with an installed capacity of 379 MWe,

represented 22% respectively. In contrast, the geothermal installed capacity in Çanakkale and İzmir remained very low.

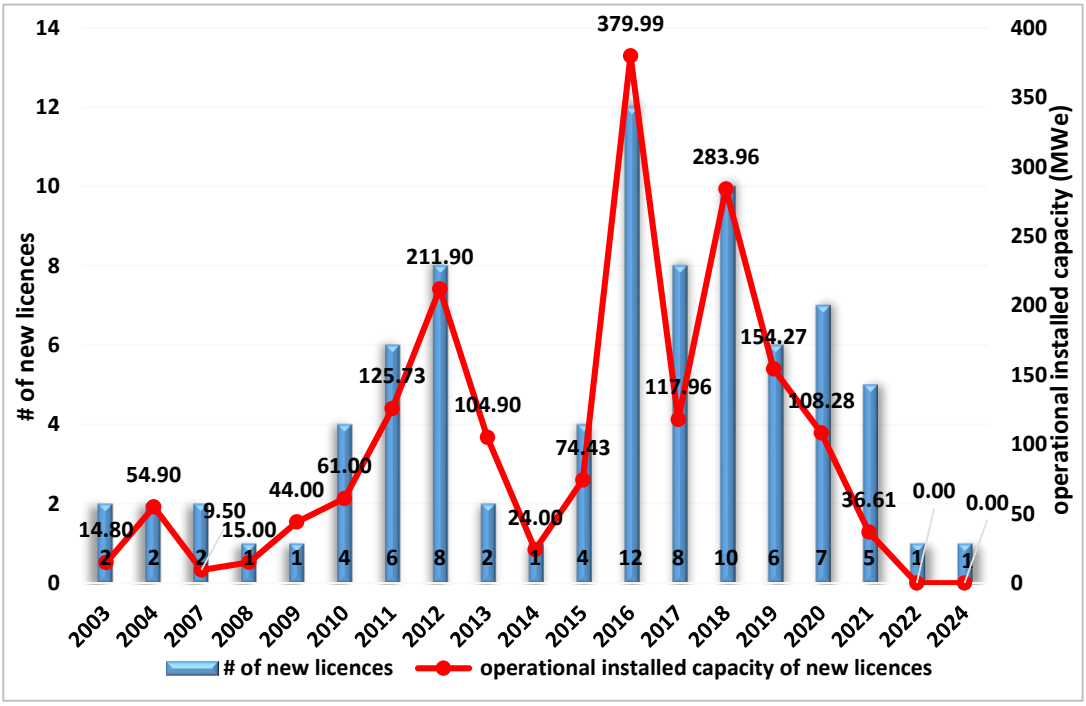

Figure 2.8. Newly licensed geothermal power plants and their contribution to operational installed capacity, 2003-2024[2,3]

Source: Author's illustration based on EMRA electricity market generation license data

As seen in Figure 2.8, geothermal energy investments in the country were on the rise, particularly in 2012, 2016 and 2018. To illustrate, in 2018, ten power plants received electricity generation licenses for a total capacity of 283.96 MWe. One of the main reasons for these capacity expansions was the existence of incentives offered to the plants under the mechanism of YEKDEM after 2010. In 2022, 92% of the operational installed geothermal capacity would be supported under YEKDEM (EMRA, 2021). On the other hand, since 2015, there has been a notable increase in the number of production and injection wells, as well as in exploration and drilling activities. Investments in research and development, funded mainly by the private sector from 2015 to 2019, totalled US$2.3 billion. For field development and

[2] Retrieved January 20, 2024, from http://lisans.epdk.gov.tr/epvys-web/faces/pages/lisans/elektrikUretim/elektrikUretimOzetSorgula.xhtml

[3] Note that 16 licenses corresponding to the installed capacity of 129.889 MWe were terminated or canceled by the authorities over time.

drilling, they were US$1.2 billion (Huttrer, 2021), which can be another factor accounting for the capacity expansion in the country between 2016 and 2019. On the other hand, capacity increases have recently remained less limited than in previous years. Indeed, the geothermal power sector has become less attractive for investors by 2022, which raises some important research questions: Why did the sector, which grew drastically with incentives after 2010, enter a period of stagnation again? Was this only due to the changes in the YEKDEM in 2021, which will be discussed later, or were there other structural problems triggering this sectoral slowdown? Undoubtedly, addressing these questions is essential for understanding the development of geothermal energy in Türkiye.

2.4.3. Geothermal Direct Utilization in Türkiye

Beyond electricity generation, Türkiye has much greater potential in direct utilization. The geothermal resources in the country are the best suited to different direct use applications, such as district heating, greenhouse heating, use in thermal facilities, hotel heating, agricultural drying, geothermal cooling and ground source heat pump applications.

By 2020, Türkiye had become the world's second-largest country, after China, in terms of installed capacity for direct geothermal energy use without heat pumps (Lund & Toth, 2021). The country's installed capacity for direct utilization was 5,113 MWt in 2022 and its target was to reach 11,150 MWt by 2025, given that its potential is estimated at approximately 15,000 MWt (World Bank Group, 2022). The distribution of direct uses of geothermal energy in 2022, also illustrated in Figure 2.9, was realized as 47.8 %, 27.8%, 24.1% and 0.4% for thermal tourism, district heating, greenhouse heating, heat pumps and geothermal drying and cooling applications, respectively (Şener et al., 2023).

Türkiye has a long history of utilizing geothermal energy for different purposes such as bathing and balneology; however, its use in district heating systems is relatively new (Parlaktuna et al., 2021). The first geothermal space heating application in the country was realized in 1964 at the Park Hotel in Gönen, Balıkesir, while geothermal

district heating systems began to develop much later, with the İzmir-Balçova project in 1996 (Baba, 2022). Despite this early experience with direct-use applications, following the enactment of Law No. 5686 in 2007, the private sector increasingly focused on electricity generation in high- and medium-enthalpy fields, while the development of new geothermal district heating projects remained very limited over time in the country (Durak, 2025).

Today, there are 18 district heating systems in Türkiye, primarily located in the Aegean region, most of which had already been planned and were under construction before 2007. According to the Turkish Geothermal Association data[4], Türkiye can heat 158,000 dwellings with geothermal energy. At this point, some regions particularly stand out for their geothermal usage (house equivalent) as a district heating option, such as İzmir-Balçova Narlıdere (38,899), Afyon-Sandıklı (30,000), Afyon-Ömer-Gecek (25,610), Kütahya-Simav (18,612) and Manisa-Salihli (10,067) in 2021 (Şener et al., 2023).

The study of Mesin and Karakaya (2023) indicates that replacing coal, gas and electricity with geothermal district heating systems in Türkiye could yield considerable economic benefits and reduce its reliance on fossil fuels for heating. Indeed, the country can reduce its gas imports by 20% and meet up to 30% of its district heating demand by utilizing geothermal energy (Richter, 2018). Similarly, Parlaktuna et al. (2021) reveal that geothermal district heating systems are the most economical option for heating. Their closest alternative is natural gas, which is approximately 1.7 times more expensive than these systems, while coal and electricity are about 2.3 and 6.06 times costlier, respectively.

Thermal tourism represents another significant application of the direct use of geothermal energy. Türkiye, home to approximately 520 geothermal spas, attracts around 23 million visitors annually, utilizing 1,763 MWt of installed geothermal capacity and generating an estimated US$3 billion in revenue for the national economy (World Bank Group, 2022).

[4] Retrieved August 20, 2023, from http://www.jeotermaldernegi.org.tr/sayfalar-Türkiye-de-Jeotermal

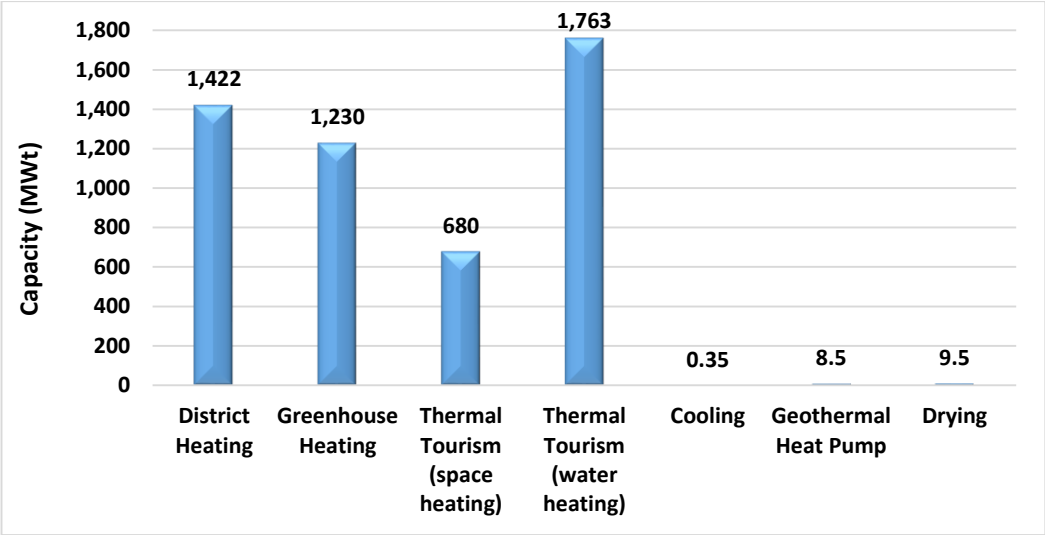

Figure 2.9. Geothermal direct utilization capacity of Türkiye in 2022

Source: Şener et al. (2023)

In Türkiye, geothermal greenhouse cultivation was first implemented in 1985 in Kızıldere-Denizli (Kaymakçıoğlu & Çirkin, 2005). In parallel with global trends, the geothermal greenhouse heating capacity in the country increased significantly over the years to 1,230 MWt and the total greenhouse area expanded to 5,293 acres in 2022 (Şener et al., 2022). While the number of Organized Agricultural Zones (OAZs) aiming to support sustainable agriculture and increase productivity has reached 41 in 2024 and out of 19 agricultural OAZs, 12 have been established as geothermal-heated greenhouses (Ministry of Agriculture and Forestry, 2024). Indeed, in recent years, there has been growing interest in the use of geothermal energy for greenhouse applications in Türkiye, largely driven by the allocation of credit loans by the World Bank to such projects, together with incentives offered by the Ministry of Agriculture (Pedrosa et al., 2026). Furthermore, low-interest investment and working capital loans offered by Ziraat Bank and the Agricultural Credit Cooperative have further stimulated this interest among Turkish investors (World Bank Group, 2023). Given that the heating costs in greenhouse cultivation can vary between 40% and 80% of total production expenses based on the growing season and location (Kendirli & Çakmak, 2010) and greenhouse heating requires relatively low temperatures, geothermal energy can offer a vast potential for Turkish farmers to reduce production costs, enhance efficiency and ensure food security. Furthermore, it can contribute significantly to local employment,

particularly by increasing women's participation in the labor force (World Bank Group, 2022).

As illustrated in Figure 2.9, geothermal heat pumps, cooling and drying applications have remained limited in Türkiye. Particularly, heat pumps, as being promising technology providing both heating and cooling with high efficiency, have not developed in the country largely due to their high capital and installation costs (Ağbulut et al., 2023). Although heat pump technology is well known in Türkiye, the low adoption of shallow geothermal systems and geothermal heat pumps can be attributed to the lack of domestic heat pumps suppliers, reliance on imported materials, absence of regulations and incentives and low public awareness and expertise (Cetin & Paksoy, 2015). Nevertheless, there are several heat-pump installations in major cities of Türkiye, used in places like hotels, schools, office buildings, shopping malls and airports.

Geothermal agricultural drying can remarkably reduce food waste and contribute to both the economy and the environment (Şener et al, 2022). The use of geothermal energy in agriculture can allow for controlling the drying temperature and enhancing product quality, in contrast to traditional sun-drying practices carried out outdoors. The regions of Sandıklı (Afyon), Şeferihisar (İzmir) and Karakurt (Kırşehir) stand out with their geothermal food drying activities in recent years. In addition to being a pioneer in district heating, Türkiye's first geothermal cooling application also initiated in İzmir Balçova-Narlıdere in 2018, providing cooling for 1,900 m² of indoor space (Baba et al., 2022).

Despite being implemented in only a few plants, the successful examples of integrated geothermal systems can be found in Çanakkale-Babadere, Aydın-Ortaklar, Germencik and Salavatlı and Denizli-Sarayköy (Şener et al., 2022). In addition to electricity generation, these integrated systems provide local economic and social benefits and can play an important role in increasing public acceptance of geothermal energy.

Today, many countries, including France, Germany, Australia and the UK, are investing heavily in the research and development of EGS-related systems and

several projects have already reached commercialization (Baba & Chandrasekharam, 2022). Türkiye also exhibits significant potential for EGS development, with an estimated technical capacity of around 400,000 MWe, of which approximately 40,000 MWe is suitable for electricity generation (Mertoğlu et al., 2023). If harnessed effectively, this substantial geothermal potential could support not only the country's future electricity production but also a wide range of direct-use applications, such as space heating and greenhouse cultivation (Şener, 2024).

Lastly, lithium extracted from geothermal fluids, which are rich in various metals and minerals, has emerged as a critical component in energy storage technologies, electric vehicles and 100% renewable energy systems **(**Elüstün, 2021). At this point, Türkiye can possess a significant potential to produce 35,000 tons of lithium annually, corresponding to nearly 10% of global production in 2024 (Richter, 2025). Similarly, its geothermal potential can provide the country with a comparative advantage in hydrogen production, which is expected to become an important energy carrier in the future. Hydrogen sulphide, a toxic and polluting component of geothermal gases, can be used as a source for hydrogen production (Haklidir & Haklidir, 2010). Indeed, the study by Karayel et al. (2022) estimates that Türkiye has the potential to produce up to 560 kilotons of hydrogen from its geothermal resources and identifies the highest potential in several Aegean provinces, including Aydın, Manisa and Denizli.

Overall, the evidence presented in this chapter indicates that Türkiye possesses substantial opportunities to expand the utilization of its geothermal resources through electricity generation, direct-use applications and emerging technologies such as lithium extraction and hydrogen production. At the same time, the recent slowdown in geothermal power investments indicates that the future development of the sector depends on more than the country's geothermal resource potential. A comprehensive understanding of geothermal development therefore requires considering the wider technological, institutional, financial, environmental and socio-economic factors that shape the sector's evolution.

CHAPTER 3

ASSESSMENT OF GEOTHERMAL ENERGY DEVELOPMENT IN TÜRKİYE BASED ON TECHNOLOGICAL INNOVATION SYSTEM FRAMEWORK

Building on the geothermal outlook and the historical development of geothermal energy in Türkiye presented in the previous chapter, this chapter analyses the diffusion of geothermal energy in Türkiye using the Technological Innovation System (TIS) framework, informed by the wider TIS literature on renewable energy technologies. In this context, it seeks to contribute to a better understanding of the development, structure and dynamics of the Turkish geothermal energy sector.

3.1. Fundamentals of TIS

The Technological Innovation System (TIS) approach builds upon the "technological systems" framework introduced by the study of Carlsson and Stankiewicz (1991) emphasizing that the dynamic interaction between agents under a specific institutional infrastructure determines the generation, diffusion and utilization of a technology.

The technological systems framework was further developed as TIS along with some prominent studies such as Jacobsson and Bergek (2004), Hekkert et al. (2007), Negro et al. (2007), Bergek et al. (2008a), Markard and Truffer (2008). Different from the technological systems concentrating on the diffusion and utilization of mainly existing or incumbent technology, TIS also centers upon the innovation system of emerging ones (Hekkert et al., 2007).

Since ensuring the sustainability of technological change encompasses multiple dimensions, the TIS framework is not limited to analysing technical aspects alone. It

also examines transformations in socio-technical processes, including user practices, regulatory structures and industrial networks (Hekkert et al., 2007; Edsand, 2017). Furthermore, TIS considers the institutional and organizational changes necessary to support technological development, while maintaining a focus on the emergence and diffusion of new technologies (Markard et al., 2012).

Even though technological systems usually go beyond geographic boundaries and have international features, national policies and knowledge transfer between the actors within the same region or country are crucial to the rapid diffusion of technology and reduction of costs (Vasseur et al., 2013). While addressing malfunction of the system rather than market failure and revealing drivers and barriers of technological innovations, TIS studies aim to inform policymakers and offer policy recommendations (Markard et al., 2012).

3.2. Structural Analysis of TIS

TIS is defined as a "*network(s) of agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse and utilize technology*." (Jacobsson & Bergek, 2004; Bergek et al., 2008a). In this definition, the technological system is mainly identified by three structural components: agents, networks and institutions. Even though this structure mostly constitutes the internal dynamics of TIS, external factors engaging with internal processes can also have an impact on the evolution of TIS (Bergek et al., 2008b).

Actors may include individuals, firms and organizations such as governmental bodies, financial institutions, universities and NGOs. At this point, a prime mover actor who is technically, financially and/or politically powerful can have a significant impact on the development of the technology or a non-commercial organization can play an important role in adopting new technologies (Jacobsson & Bergek, 2004).

The networks with the interactions and cooperative relationships between the actors or a more complex actors' organization (Wieczorek & Hekkert, 2012), can be categorized as "learning" or "political" networks. While learning networks aim to

develop and diffuse technical knowledge between suppliers, users, firms and researchers, political networks comprising different actors sharing a set of common beliefs seek the power to influence political decisions (Bergek et al., 2008b). Moreover, formal networks enable firms and other organizations to come together and contribute to achieving common targets and solving some technology-specific problems (Musiolik et al., 2012).

Institutions include formal rules such as regulations, laws, property rights and some norms on culture and tradition. They play an important role in the reduction of market uncertainty along with additional information, management of conflicts, promotion of cooperation and introduction of incentives for new technologies (Edquist & Johnson, 1997; Bento & Fontes, 2015). While "internal" institutions are derived from activities of system actors such as lobbying, expectation management, negotiation of internal standards; "external" ones such as international energy agreements are not set by these actors and are somehow separate from TIS, but they can have an impact on the stabilization of TIS (Markard &Truffer, 2008).

3.3. Functional Analysis of TIS

The structural analysis of TIS enables researchers to gain insight into the conditions under which technological transition occurs. Nonetheless, the identification of the main problems in a TIS necessitating specific policy recommendations solely based on the structural components can be misleading since evaluating the strengths and weaknesses of a particular structural element or combination of elements is difficult without revealing its impacts on the innovation process (Bergek et al., 2008a; Eleftheriadis & Anagnostopoulou, 2015). Therefore, the concept of "*system functions*" is offered mainly by the studies of Bergek et al. (2008a), Hekkert et al. (2007) and Negro et al. (2007) to evaluate the success of TIS as a whole and constitutes a robust conceptual basis for empirical TIS research (Hsieh & Liu, 2025).

The proper operation of TIS functions is a prerequisite for successfully implementing new technology. These functions serve as an intermediary between the structural components of the TIS and its overall performance (Jacobsson & Bergek, 2004).

Indeed, the activation of these functions fosters the development of structural elements, which in turn reinforce the functions themselves (Leitch et al., 2019).

As illustrated in Figure 3.1, TIS analysis begins by defining the system and then examines its structural components. The performance of the innovation system is subsequently assessed through seven key system functions whose definitions and indicators are presented in Table 3.1, such as "*knowledge development and diffusion*", "*entrepreneurial experimentation*", "*influence on the direction of search*", "*market formation*", "*resource mobilization*", "*legitimation*" and "*development of external (positive) economies*". If some of these functions are not fulfilled, the performance of TIS is adversely affected. Indeed, the effectiveness of these functions and their interactions with each other constitutes a critical determinant of the system's ability to achieve its common objectives (De Jesus Fernandez & Watson, 2022). Therefore, identifying systemic barriers and weakly performing innovation functions is crucial for developing effective policies that can accelerate technology diffusion (Vasseur et al., 2013).

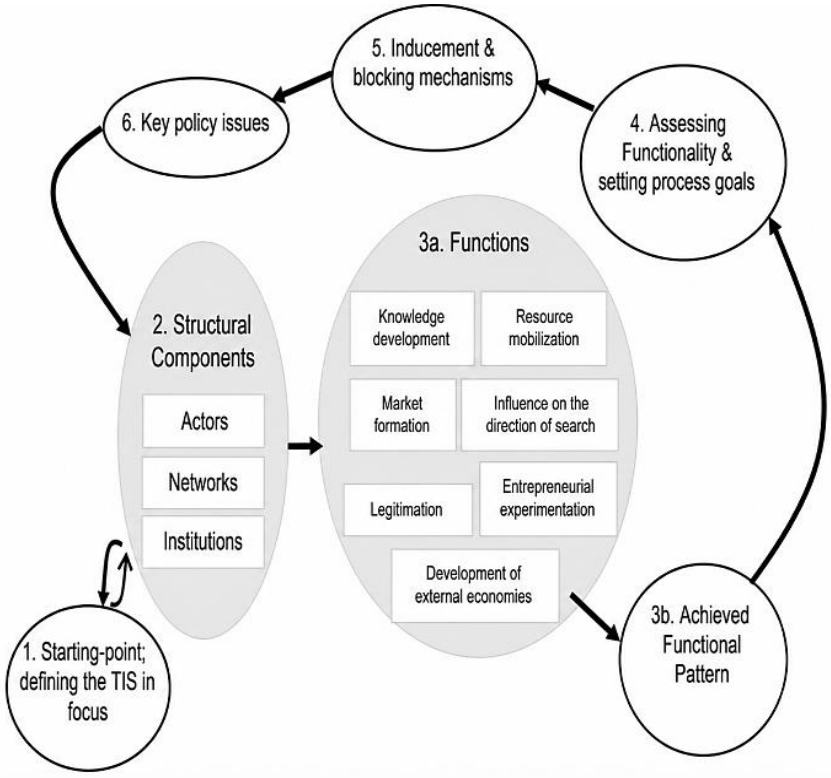

Figure 3.1. The scheme of TIS analysis

Source: Bergek et al. (2008a)

Table 3.1. Description of the seven key functions of a TIS and their indicators

Function	Description of function	Further indicators for mapping function
Knowledge development and diffusion	Unpacking the processes of learning (Learning by searching, doing, using and interacting)	R&D and joint projects, activities of industry associations, scientific publication and patenting figures, websites, workshops, international conferences and linkages among key stakeholders
Entrepreneurial experimentation	Developing new technologies, creating new markets and networks	New entrants, size of firms, diversification of activities of incumbents, number of different types of applications, export activities
Influence on the direction of search	Offering incentives and/or pressures for firms and organizations to enter the TIS	Visions and beliefs in growth potential, press coverage, regulatory pressures and policy targets
Market formation	Assessing which phase the market is in (nursing, bridging or mature) and offering relevant institutional support	Market size, import share, financial market incentives (regulation/stimulation programs), regulations/tax regimes, actors' strategies and other drivers such as institutional stimuli, purchasing processes, etc.
Resource mobilization	Providing financial capital, competence/human capital and complementary assets to the TIS	Financial resources (e.g. subsidies for and investments in technology), human resources, physical resources, foreign direct investment
Legitimation	Enhancing social, industrial and political acceptance of the TIS with the support from advocacy coalitions	Recognition of (societal) benefits of the technology, public interest/acceptance, governmental statements, activities to align institutional setting, lobby activities for/against the technology, regulatory and fiscal instruments (e.g. FITs)
Development of positive external economies	Creating positive external economies such as labor markets, intermediate goods and service providers, as well as knowledge spill over effects	Knowledge flows, cost reductions, political power, legitimacy/resolution of uncertainties

Source: Author's compilation based on Praetorius et al. (2010), Gosens and Lu (2013), Vasseur et al. (2013), Eleftheriadis and Anagnostopoulou (2015), Bento and Fontes (2015)

As summarized in the study of Wieczorek et al. (2013), knowledge development is critical for the innovation process and entrepreneurs are necessary to transition new knowledge, networks and markets into new business opportunities. While guidance of the search provides a clear development direction for emerging technologies, cost reductions and entrepreneurial incentives are crucial for stimulating new market entry and enabling the transition from nursing to bridging and eventually mature market formation. Financial, human and physical resources are indispensable for all activities in the innovation system and investing and ensuring adaptation to new technology requires a certain level of legitimacy. On the other hand, the development of positive externalities indicates the power of the collective dimension of the TIS

and reveals the extent to which the other functions contribute to offering positive externalities (Bento & Fontes, 2015).

In addition to the common functions frequently applied in the TIS literature, as summarized in Table 3.1, several extended versions of this list have been proposed in different studies for specific systems, highlighting the flexible and adaptive nature of the TIS function approach. To illustrate, the study of Edsand (2017), determining the barriers to wind energy development in Colombia as a developing country context, adds "*creating adaptive capacity*" into baseline function list, splits resource mobilization into two parts as "*domestic*" and "*internationa*l" and creation of legitimacy as "*formal*" and "*informal lobbying*". On the other hand, even though the definitions and indicators of these innovation system functions differ, there is a broad consensus in the literature regarding the importance of some specific functions (Meelen & Farla, 2013).

3.4. TIS Literature on Renewable Energy Technologies

The TIS approach is particularly well-suited for emerging fields such as renewable energy technologies, for which there are market and technology uncertainties and ex-ante boundary setting of the system is not possible since it is not definite how technology will be developed and who will adopt it (Coenen & López, 2010). Despite the initial focus of TIS research on renewable energy technologies being largely on developed countries (Kebede & Mitsufuji, 2017), there has been a remarkable increase over time in the studies implementing the TIS framework also for developing ones.

Today, the TIS literature encompasses a substantial body of research examining the development and diffusion of various energy technologies for a single-country or cross-country comparisons. To illustrate, Negro et al. (2007) examine the factors contributing to the slow diffusion of biomass conversion technologies in the Netherlands. The study highlights the importance of government policies, such as fixed feed-in tariffs and co-digestion incentives in enhancing key TIS functions, namely the guidance of the search, market formation and resource mobilization,

particularly in contexts where entrepreneurial activities are constrained by institutional instability and weak collaboration between academia and project developers. On the other hand, Hillman et al. (2008) analyse the development of biofuel technologies in the Netherlands, in comparison with Sweden and reveal how crucial the well-functioning system functions and the formation of cumulative causation are for the diffusion of energy technologies, as evidenced by the Swedish experience. Nonetheless, Tigabu et al. (2015), in their study on the development of biogas technologies in Rwanda and Kenya, conclude that national and international factors play a more significant role in the early-stage technology diffusion rather than technological capacity or the interrelation of system functions. The study further emphasizes the importance of well-targeted international assistance to support the advancement of renewable energy technologies in these countries.

Regarding wind energy technologies, Bento and Fontes (2015) focus on the emergence of the Portuguese wind sector as an example of a "latecomer" in technology development. They demonstrate that the functional analysis of TIS, typically applied to pioneer countries, can also explain diffusion processes in follower contexts. However, complementary components, such as local knowledge accumulation and experimentation, should be taken into account to enhance the ability to adopt new technologies. The study also highlights that Portugal's success as a fast follower resulted from aligning robust political commitment with the capacity to internalize foreign technologies, leveraging national competences, resources and global networks. On the other hand, Edsand (2017) explores the obstacles to wind energy diffusion in Colombia through an extended TIS framework and reveals that the performance of system functions can be influenced by broader socioeconomic, environmental and political factors endogenous to the system. From an example of developing country with significant renewable energy potential, Wandera (2021) argues that the limited diffusion of small wind turbine technology in Kenya, despite its relatively long history, can be attributed to the weak performance of several key TIS functions, particularly the mobilization of financial resources, the guidance of the search and the creation of legitimacy for these technologies.

For solar energy, Vasseur et al. (2013) drawing insights from the Japanese case, characterized by a strong industrial base and a large domestic market for

photovoltaics (PV), emphasize the crucial role of international factors such as trade flows, foreign direct investment and cross-border knowledge exchange in facilitating the diffusion of solar energy technologies in the Netherlands. Similarly, Quitzow (2015), analysing the co-evolution of PV technologies in Germany and China, illustrates how dynamic and reciprocal interdependencies between a developed and an emerging economy can reinforce the diffusion of solar technologies in each individual country. On the other hand, Kebede and Mitsufuji (2017) explores how adopted technologies from industrialized countries can be localized, utilized and evolved to further innovations using the Ethiopian solar case. The study emphasizes that well-designed policy interventions are vital to stimulate market formation in the technology-receiving countries by promoting local industrial development while simultaneously strengthening absorptive capacity and technology skills through the cooperation of academia and researchers.

Apart from these renewable energy technologies, there exists only a limited body of research analysing the development of geothermal energy using the TIS framework. Among these studies, Leitch et al. (2019) demonstrate that the established oil and gas sector in Alberta, Canada can support the development of geothermal energy. Indeed, this study introduces a new function into the TIS framework, referred to as "*system complementarity failures*," besides seven common ones in the TIS literature, with particular emphasis on the underutilized opportunities for socio-technical complementarities across the existing and new systems. Particularly, it reveals that complementary structural overlaps between the geothermal and oil/ gas sectors, such as shared technical and non-technical skills (drilling techniques, engineering experience, project management expertise, market knowledge), application of similar political networks and regulatory frameworks, comparable resource exploration risks and similar technologies in terms of sub-surface data and sub-surface wells, can facilitate the development of geothermal industry by reinforcing the functions of the emerging geothermal TIS in Alberta.

In another study on geothermal energy TIS mainly employing the seven key TIS functions, De Jesus Fernandez and Watson (2022) examine how Mexico's shift in energy policy away from renewable energy sources to fossil fuels along with the new

administration in 2019 has influenced the development of geothermal and solar PV technologies in the country as a comparative analysis. Their findings indicate that changes in federal government priorities had the greatest impact on "*market formation*" and "*legitimation*" within the geothermal TIS. The new policies emphasizing the preservation of state-owned utilities consequently favoured geothermal development over solar PV, as geothermal energy in Mexico remained almost entirely under state ownership. Nonetheless, inadequate public investment in renewable energy research, the shortage of skilled academics and practitioners and the limited engagement of international firms amid unfavourable market conditions collectively hindered the advancement of both solar and geothermal technologies in the country.

Based on the geothermal TIS approach utilizing the seven key functions, Hsieh and Liu (2025) examine the factors constraining the diffusion of geothermal energy in Taiwan, despite the country's substantial resource potential and ambitious policy targets. Drawing on the functional analysis of the TIS, the study concludes that limited market incentives, high costs, regulatory obstacles and social opposition collectively account for the stagnation in geothermal energy development in the country.

Regardless of the type of renewable energy technology, all these studies explicitly or implicitly indicate that the diffusion of such technologies is determined by the interaction among technologies, actors, institutions and markets (both domestic and international) as well as socioeconomic, environmental and political factors. Innovation processes in renewable energy technologies are now increasingly developing beyond national borders within transnational networks and global value chains. Even though the trajectories of countries developing or adopting these technologies differ, it is widely acknowledged that strong synergy among the system functions such as knowledge creation, market formation, legitimacy building and resource mobilization are critical for the success of TIS. Furthermore, while TIS analysis provides valuable guidance for policy formulation, well-designed policies, in turn, can foster the enforce and advance the evolution of TIS, which indicating a dynamic and bidirectional relationship. Even though these discussions are also

relevant to geothermal energy technologies, the concentration of geothermal resources in a limited number of countries makes national policies that promote the well-functioning of the system particularly important for the development of these technologies.

Geothermal energy development is a complex socio-technical process that depends not only on resource availability and technological capabilities, but also on the interaction of multiple actors, institutions, policies, financial mechanisms and market dynamics. The TIS framework is particularly suitable for analysing such processes because it enables a systemic examination of how innovation emerges, diffuses and matures within a specific technological domain. Thus, this study adopts the TIS framework to examine the diffusion of geothermal energy in Türkiye, a country that has experienced remarkable growth in geothermal installed electricity capacity over the past decade, but has shown signs of slowdown in recent years. To the best of our knowledge, this study constitutes the first application of the TIS approach to geothermal energy in the context of Türkiye. Accordingly, it seeks to make a valuable contribution to the literature by providing a systematic and comprehensive analysis of the Turkish case.

For TIS analyses, in addition to the seven main functions presented in Table 3.1, this research also incorporates system complementarity failures between the oil and gas sectors and the geothermal sectors following the approach of Leitch et al. (2019) while accounting for the diffusion of geothermal energy in Türkiye. Furthermore, it seeks to offer insights into the interactions among institutional, technological and social factors that influence the diffusion of a renewable energy technology within the context of a developing and resource-rich country as a case study. Finally, by identifying the performance of geothermal TIS functions and their interactions, this study aims to provide a basis for policy recommendations that support the further development of the geothermal energy in Türkiye.

3.5. Development of Geothermal Energy in Türkiye based on TIS Framework

Considering that MTA conducted its first geothermal exploration in Balçova-İzmir in 1962, the first geothermal heating system was established in Gönen-Balıkesir in 1964

and geothermal power generation projects started in Kızıldere-Denizli in 1974 (Herrera-Martínez, 2017), Türkiye has made continuous efforts for many years to harness its geothermal potential. Indeed, the period between 1970 and 1980 marked a phase in which high-temperature geothermal fields were discovered by MTA (Akkuş, 2017). As of 2004, geothermal resource exploration activities were significantly intensified, with annual drilled geothermal exploration increasing from approximately 2,000 meters to 28,000 meters (TÜBA, 2020). Nonetheless, all these developments were public-sector-driven at that time. The first private geothermal energy power plant was established in 2006 and the technology diffusion was realized very slowly until 2008.

In terms of the *institutions*, the enactment of the Utilization of Renewable Energy Resources for the Purpose of Generating Electricity Law (Law No. 5346) in 2005, the Geothermal Resources and Natural Mineral Waters Law (Law No. 5686) in 2007 and the implementation of a feed-in tariff mechanism YEKDEM in 2011 under Law No. 5346 were the main drivers for attracting private sector investments, so the rise of geothermal power generation in the country. Furthermore, several geothermal-specific targets have been integrated into national energy strategies and policy documents, as previously discussed, which reflects the government's continued policy commitment to geothermal energy development.

Considering the *actors*, the geothermal power sector in Türkiye has evolved as a fragmented market. ZORLU, GURMAT, KIPAS, CELIKLER and SARAY&ACARSAN (GREENECO) are the leading companies in the geothermal power sector. These companies also invest in other renewable energy technologies, including coal, hydropower and wind. On the other hand, some small and non-institutional firms are also operating in the market. The government's national energy policy is implemented by the MENR and, as discussed earlier, a range of governmental bodies are responsible for geothermal activities in the country from exploration to operation. As another key actor, some universities also make significant contributions to the development of geothermal technologies through collaborative research and innovation carried out with private sector partners.

Regarding political *networks* or advocacy coalitions in Türkiye, there are two prominent geothermal associations whose members include various geothermal companies: The Geothermal Power Plant Investors Association (JESDER), established in 2014 and the Geothermal Energy Association (JED), founded in 2020. JED mainly consists of large and institutional firms that parted later from JESDER, indicating again the sector's fragmented development. Nonetheless, as an example of political network, both associations make ongoing efforts to bring geothermal energy onto the political agenda and ensure that it is reflected in national energy policies. Apart from JESDER and JED, the Geothermal Investors Association (JEMYAD) works to coordinate geothermal investors, advocate for their interests at national and international platforms and promote the enactment of a more comprehensive and resilient legislations for the development of the Turkish geothermal sector. Furthermore, the Türkiye Geothermal Association supports the advancement of scientific knowledge and enhances awareness of the sector's potential through its academic research and publications. As can be seen, despite the presence of several associations, geothermal sector in Türkiye lacks a unified representative body.

Regarding technological equipment, the Turkish geothermal energy sector remains heavily dependent on foreign technologies, highlighting the need to develop domestic manufacturing capabilities for high value-added equipment. Even if the local manufacturing incentive scheme for specific components, such as turbines, generators, power electronics, led several binary equipment retailers to manufacture, its success has remained limited (Halaçoğlu et al., 2017). Turboden, Ormaturk, Exergy and Atlas Copco are some companies manufacturing geothermal turbines with local components in Türkiye (TÜBA, 2020). Furthermore, R&D activities in the geothermal sector have not yet been at the desired levels compared to other REs. As seen in Figure 3.2, illustrating the number of patent evaluations for renewables, solar and wind have been the main technologies with increasing innovation efforts, particularly after 2011 and geothermal has lagged significantly in this competition. As emphasized by JESDER (2025), although geothermal power plant technologies used in Türkiye are compatible with modern global standards, limited domestic manufacturing capacity continues to create cost and logistical challenges for investors and constrains the implementation of new projects. Moreover, while local

investors have accumulated significant sectoral knowledge and experience, this expertise has not yet been sufficiently translated into domestic technological development through R&D activities. Nonetheless, the country's knowledge development and diffusion efforts have remarkably increased over time. Specialization in the oil and gas sectors provided an advantage for geothermal drilling activities. Firms have significantly accumulated their human resources, experience and know-how and the country has intensified its efforts of *knowledge development and diffusion* in the last decade.

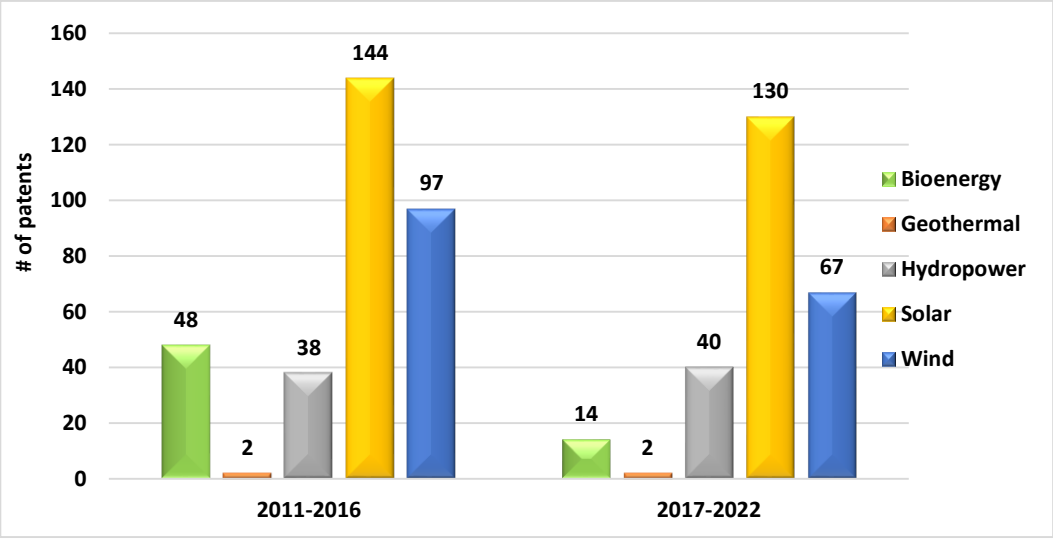

Figure 3.2. Renewable energy technology patents in Türkiye, 2011-2022

Source: Author's illustration based on IRENA (2024a) data

The first geothermal R&D centre for aiming localization of machinery and equipment was established in 2020. The Scientific and Technological Research Council of Türkiye (TUBITAK) has promoted R&D studies for geothermal energy technologies and direct utilization applications in the scope of the GEOTHERMICA project, consisting of 20 geothermal energy research and innovation program owners and managers from different countries, to strengthen the European geothermal sector. The partnerships between technology developers and academia have accelerated through the national research centres at universities and some international projects such as GECO, GeoSmart, GEOPRO, SUCCEED executed by the partnership of ZORLU as a pilot plant operator from Türkiye and other national and international researchers (TÜBA, 2020). Annual national or international meetings and

conferences supported by the government and developers or associations have been effective in knowledge exchange, collaborations with other researchers and keeping track of the latest developments in the geothermal industry.

Concentrating on *entrepreneurial activities and market formation* for the Turkish geothermal power sector, it is remarkable that there have been only two new entrants after 2021, still not operational, which can be partly attributed to the market structure. The market has a fragmented structure with a group of small and large firms. Figure 3.3 shows ten prominent companies in the geothermal electricity market in 2024. These companies are ambitious to conduct R&D studies and are open to further industrial cooperation with their national and international partners to develop geothermal energy. They are also keen on innovative and efficient plant design. To illustrate, the Kızıldere-3 plant operated by ZORLU received the 2018 American Council of Engineering Companies Award for its engineering excellence. With 45 plants, these ten companies constitute 84% of the installed capacity in 2024. In addition to the energy sector, these firms operate in many fields, such as construction, cement, textiles, real estate. Remarkably, the market share of ZORLU is even more than the total percentage of 19 companies, with 22 plants regarded as small ones in terms of their installed capacity (OTHERS).

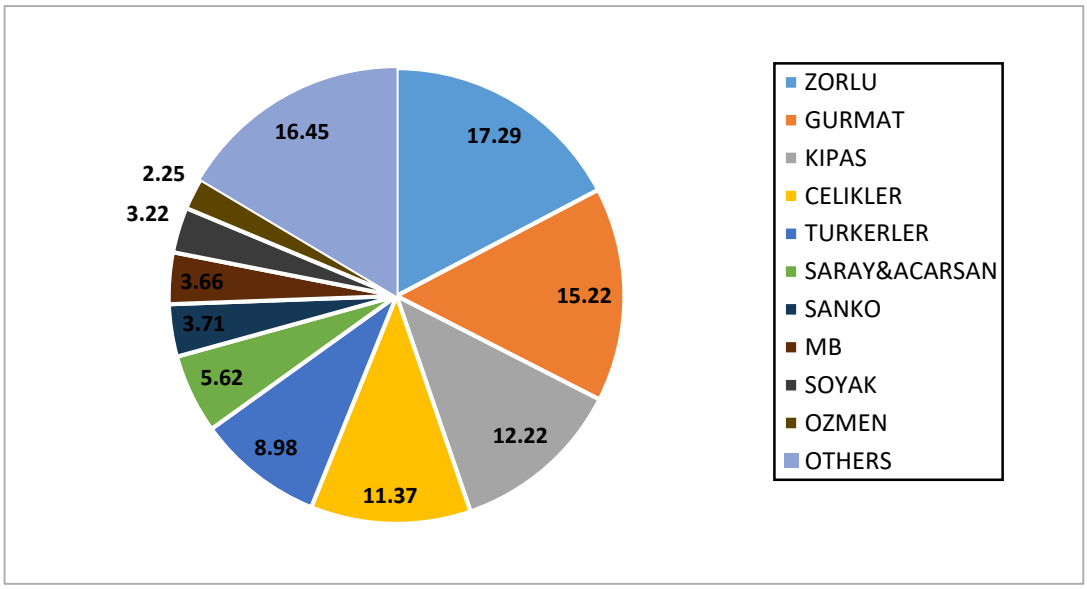

Figure 3.3. Distribution of company-based geothermal installed capacity in 2024 (%)

Source: Author's illustration based on EMRA electricity market generation license data

All these figures indicate that the development of geothermal energy in Türkiye has been shaped mainly by the initiatives of a limited number of pioneering firms, rather than reflecting a broad and inclusive expansion across the sector. Unlike other REs, foreign direct investments remained relatively limited for geothermal energy. As a promising development, the Dutch company TRANSMARK and the French company ALBIOMA entered the geothermal power market only after 2021. Nonetheless, as these examples illustrate, foreign investment has tended to enter the market primarily through the acquisition or transfer of existing projects, rather than through direct engagement in early-stage exploration and development activities.

The government plans and strategy documents concerning renewable energy development have been practical tools for *influencing the direction of the search* for investors. Indeed, the absence of clear and long-term targets set by the governments that outline the desired percentage of the related energy mix, along with a specified timeline for achieving this goal, can pose a significant barrier to the widespread adoption of the technology (Edsand, 2017). Türkiye included its geothermal-based goals in the policy documents (Şahin, 2021), such as the National Climate Change Action Plan (2012), National Renewable Energy Action Plan (2014), Tenth Development Plan (2014-2018) and National Energy Strategic Plan (2015-2019). This policy orientation instilled a certain degree of confidence in the development of the geothermal sector and encouraged new market entries. However, stronger political commitment, together with explicit geothermal targets, could have further reinforced entrepreneurs' expectations. As the most recent policy document, the National Energy Plan (2022) sets a target stating that "*the installed capacity of geothermal and biomass power plants will reach 5.1 GW in total by 2035*." This approach has been strongly criticized by geothermal associations that there are well-defined and individual targets in this policy document for other renewables such as solar (52.9 GW), hydro (35.1 GW) and wind (29.6 GW), but a common one for geothermal along with biomass (5.1 GW), which does not reflect the future potential of geothermal and can discourage the investments[5]. This global issue for geothermal energy is particularly emphasized by the IEA (2024, p. 10), which states: "*If*

[5] Retrieved January 6, 2025, from https://www.enerjigunlugu.net/ali-kindap-2030-jeotermal-hedefi-potansiyelimizin-cok-altinda-52757h.htm

geothermal is to realise its potential, governments need to move it up the national clean energy policy agenda with specific goals and roadmaps and recognise its unique features as a source of firm, dispatchable low-emissions electricity and heat."

As an incentive scheme effectively implemented since 2011, YEKDEM has been the most successful driver of the rapid growth of geothermal power generation in Türkiye. As a support mechanism, it contributed both to *influencing the direction of search and to market formation* within the Turkish geothermal sector. Indeed, the Turkish experience offers a clear example of how renewable energy capacity can expand under supportive government policies. Between 2011-2020, these fixed and USD based feed-in tariffs offered the guaranteed and long-term income for the investors. The small firms, which had not previously engaged in the energy sector but pursued incentives, quickly penetrated the geothermal market after 2010. Nonetheless, following the changes introduced to YEKDEM in 2021, under which incentives were denominated in Turkish lira rather than foreign currency and set at 540 TRY/MWh for geothermal projects entering operation between 2021 and 2025, the Turkish geothermal power sector lost its appeal to investors.

Between 2021 and 2023, electricity market prices rose significantly due to inflationary pressures, the depreciation of the Turkish lira and rising natural gas prices, eventually surpassing feed-in tariffs and thereby reducing the attractiveness of the YEKDEM scheme for new investors (Kirkil et al., 2026). In this context, Öznazik (2022) reveals that electricity generation prices of geothermal power plants decreased by over 60% after this change, which accounts for why new investments in the market reached a standstill. While these discussions were ongoing, amendments were made to YEKDEM in 2023 and a price floor of 94.5 USD/MWh was introduced for geothermal projects entering operation during 2021-2030 in addition to the implementation price of 2,020 TRY/MWh (Hakyemez, 2023). In this way, it was aimed to protect the feed-in tariff in local currency against exchange rate fluctuations.

The successive changes in the YEKDEM have been frequently criticized for creating uncertainty for investors seeking to build their future business strategies under stable

and long-term policy support. Another criticism is that, assuming a 5-year construction period, a plant approved today would be commissioned no earlier than 2031 and therefore would not be eligible for the 15-year YEKDEM support scheme; accordingly, the deadline of YEKDEM should be revised specifically for geothermal projects.[6] In this regard, the Turkish geothermal power sector primarily reflects bridging market formation, as the technology has expanded beyond the niche stage but still relies on supportive institutional, financial and regulatory conditions to sustain further growth.

Unlike electricity generation, the lack of systematic national incentives for direct utilization has been a significant obstacle to unlocking the country's full geothermal potential. Indeed, the rapid expansion of the electricity sector over the last decades has revealed a major imbalance in Türkiye's geothermal development (Durak, 2025). Although around 90% of the country's geothermal resources are suitable for direct-use applications, investments have largely concentrated on high-enthalpy fields for electricity generation. As a result, direct-use applications such as district heating experienced very limited expansion during the same period, leaving a substantial portion of the country's geothermal potential underutilized. Despite some promising international cooperation initiatives, such as the Türkiye-Denmark Strategic Sector Cooperation Program launched in 2017, the heating law discussed for years in Türkiye has still not been enacted.

Resource mobilization is vital for geothermal energy investments with longer payback periods, higher construction costs and risks. Offering incentives or financial tools to reduce exploration risks can attract investments in new geothermal projects. In the Turkish geothermal market, there is no government-supported risk mitigation scheme, but international institutions offer some funds to investors. As addressed earlier, the Geothermal Development Plan funded by the World Bank flows capital in the form of a loan facility for resource development and a Risk Sharing Mechanism to cover 40% to 60% of the cost of failed wells. Regarding tax incentives for physical capital, geothermal power generation plants holding an investment incentive

[6] Retrieved April 29, 2026, from https://www.jeotermalhaberler.com/jeotermal-sektorunden-yekdem-2040-talebi/

certificate can purchase new machinery and equipment without paying value-added tax (VAT) and they are also exempt from customs duties by Ministry of Industry and Technology when importing equipment. Some other incentives and exemptions currently applicable for oil exploration and drilling, such as exemption from fuel-related VAT and special consumption tax can also be provided for geothermal drilling (Akkuş & Alan, 2016). Unlike many other renewable energy technologies, geothermal energy development depends heavily on interdisciplinary engineering expertise, requiring the coordinated involvement of geology, geophysics, drilling, mechanical, electrical, environmental and reservoir engineering throughout the entire project lifecycle. Regarding human capital accumulation in the geothermal energy sector, the number of qualified engineers and technical personnel to install and maintain a plant remains inadequate but continues to increase.

Along with the climate change objectives, *legitimizing* geothermal energy as an energy mix option has been included in some governmental documents. Furthermore, geothermal associations and developers accelerated their lobbying activities to incentivize further geothermal energy development. They have exerted their political power to influence government decisions, as observed in the latest change in the YEKDEM while emphasizing that the incentive scheme is a prerequisite for increasing geothermal power capacity. They also continue to stress the necessity of incentives in direct utilization on every political platform. Nonetheless, low social acceptance among the locals has continued to be a significant barrier to initiating a new project and it is quite common to come across news of public protests in media against geothermal energy. Indeed, the dense concentration of geothermal power plants in a limited area of the Aegean Region, overlapping with key agricultural zones is the one of the main reasons of the environmental problems (TÜBA, 2020). Still, there were no public complaints during earlier periods and the geothermal projects were executed without local resistance (Serpen & DiPippo, 2022). The rapid penetration of many companies into the market to receive a share from incentives and their attitudes demonstrating little or no environmental awareness have sparked anti-geothermal movements in some regions of the country over time. Most locals still insist that geothermal energy damages the environment and agricultural production, as indicated in the recent studies of Tolunay and Erden (2021) and

Öztürk and Çobanoğlu (2023). On the other hand, long negotiation or lawsuit processes with landowners or local communities still prevent developers from making geothermal investments in Türkiye.

As noted by the IEA (2024), the oil/ gas and geothermal sectors have substantial overlaps in competencies related to drilling and surface operations, skills, data management, technology and supply chain operations, allowing countries to harness cross-sectoral synergies. Türkiye's geothermal development has, to some extent, benefited from the *complementarity between the oil and gas sectors.* Experience gained from earlier hydrocarbon exploration and production projects, together with the adaptation of oil and gas subsurface technologies, has contributed to lowering input costs and improving the overall economics of geothermal projects (Pedrosa et al., 2026). As another inter-sectoral synergy, the utilization of depleted or abandoned oil and natural gas wells for geothermal applications, by harnessing their heat content or hot reservoir fluids, has attracted growing attention in Türkiye in recent years as a promising development. Since the drilling constitutes a major component of geothermal project costs, the reuse of these wells can significantly reduce investment expenditures (Aydin & Merey, 2021). In particular, repurposing abandoned oil wells in the south-eastern of Türkiye mostly for geothermal direct utilization could substantially contribute to the socioeconomic development of these regions (Kaplanoğlu et al., 2020). However, given that major oil fields in the south-eastern region are expected to reach depletion or abandonment between 2021 and 2040, the lack of regulatory frameworks addressing their potential utilization for geothermal purposes (Merey, 2021) constitutes a key sectoral complementarity failure for geothermal energy. Additionally, the absence of comprehensive techno-economic analyses represents another major barrier, despite the country's substantial accumulated knowledge and expertise in the oil and gas sectors.

In terms of *positive externalities,* each new entrant to the Turkish geothermal market has benefited from the opportunities, accumulated experience and technology knowledge offered by the incumbent firms. The expansion of direct utilization applications has provided new employment opportunities to the locals. Particularly, the number of women and young people, working in geothermal-heated greenhouses

has increased remarkably in recent years (Richter, 2020). Nonetheless, considering the country's geothermal potential, the positive externalities have remained limited due to the malfunctioning of specific TIS functions or weak synergy among them.

3.6. Conclusion and Implications for Türkiye's Geothermal TIS

Over the past decade, Türkiye's geothermal power capacity has expanded substantially, positioning the country among the fastest-growing geothermal markets worldwide. Although this development path may be regarded as a notable success story, it is nevertheless evident that Türkiye could have achieved considerably more, given the country's remarkable resource potential not only for power generation but also for direct utilization.

Based on the insights derived from the structural analysis of the Turkish geothermal TIS, the country's geothermal sector is primarily characterized by significant institutional fragmentation and limited coordination among actors and networks. This results in the lack of the collective political influence, as observed in other renewable industries such as solar and wind and which in turn constrains its capacity shape long-term policy direction and changes to the regulatory framework. Indeed, this sectoral and institutional structure also weakens the effectiveness of some core TIS functions, notably direction of search and legitimation of geothermal energy.

As revealed in the functional analysis of the Turkish geothermal TIS, although incumbent companies have contributed significantly to sectoral learning, information exchange and entrepreneurial activities at both national and international platforms, the country's overall capacity for domestic geothermal innovation has remained limited and Türkiye continues to rely heavily on imported geothermal components. In addition to constrained domestic manufacturing capabilities, the insufficient translation of sectoral expertise into R&D-driven technological development continues to hinder sectoral growth.

The lack of explicit geothermal-specific targets in national energy policy documents, in contrast to other renewable energy sources, undermines the direction of search for

investors as it provides weak signals regarding future technological and market priorities. Indeed, the development of long-term policies directly targeting geothermal energy can significantly strengthen sectoral networks, foster the spill over of skills and expertise among the stakeholders and contribute to the legitimization of geothermal energy at both the national and local level.

Geothermal energy investments, which still involve substantial upfront capital costs, continue to remains largely dependent on the availability of financial support mechanisms. In the Turkish case, international funds have played an important role in the rapid diffusion of geothermal energy by functioning as a risk-mitigation mechanism that enables resource mobilization. On the other hand, YEKDEM, which previously served as the key driver of geothermal power capacity expansion and investor confidence by supporting market formation, now acts as a constraint on further market development. This highlights the need to revise the current incentive scheme so that it better reflects evolving market dynamics and technological developments specific to the geothermal sector.

The lack of a legal framework and systematic national incentive schemes for geothermal direct-use applications constitutes a significant barrier to resource mobilization, strategic guidance and market development in the country. As a result, the increasing financial uncertainty, combined with the inherent risks of geothermal projects, discourages investors from undertaking new investments given their high upfront costs. As a market formation failure, despite the extensive technical expertise the country has accumulated over many years in the oil and gas sectors, its systematic deployment for geothermal applications has largely remained limited, primarily due to the absence of enabling regulatory frameworks.

Consistent with evidence from many other TIS studies on renewable energy technologies, weak performance in certain TIS functions has directly or indirectly impeded the functioning of others, ultimately shaping geothermal development and influencing the pace of market maturation in Türkiye. Furthermore, evidence from the Turkish geothermal TIS suggests that well-designed policy interventions are essential not only for system development, but also for maintaining the effective

functioning and alignment of system dynamics. Finally, while the early growth of the Turkish geothermal power sector was driven largely by financial incentives, particularly through the guidance of the search function of TIS, the long-term sustainability of geothermal development increasingly depends on strengthening other innovation system functions, particularly those that promote technological knowledge and learning, reduce costs, improve operational efficiency, enhance domestic manufacturing capabilities and expand geothermal direct-use applications. Taken together, these findings highlight the critical role of complementarities and dynamic interactions among TIS functions in shaping the resilience and long-term evolution of the energy technology systems.

CHAPTER 4

OPPORTUNITIES AND CHALLENGES OF GEOTHERMAL ENERGY DEVELOPMENT IN TÜRKİYE

To fully realize the potential benefits of geothermal energy, it is necessary to effectively address the institutional, financial, technical and social aspects of the resource. This chapter examines the opportunities and challenges of geothermal energy in Türkiye, incorporating the perspectives of key stakeholders through semi-structured interviews a complementary study to the previous TIS chapter. In doing so, it aims to further elucidate the sectoral drivers and barriers shaping geothermal development, while offering deeper insights into the country's current and future geothermal outlook.

4.1. Literature on Opportunities and Challenges of Geothermal Energy Development

Unlike other forms of renewable energy sources, geothermal energy is characterized by its independence from weather and climate conditions. Furthermore, it stands out with a higher capacity factor ranging from 60% to 90% (Kabeyi, 2019), compared to average values of about 14% for solar and 25% for wind (Li et al., 2015). With its potential for continuous electricity generation and inherent storage capability, geothermal energy represents a reliable and cost-effective source of baseload power available on demand (Fridleifsson, 2001). Besides non-intermittent electricity generation, geothermal energy offers also many other advantages to resource-rich countries, such as allowing energy diversification, leading to stable electricity prices, offering a clean energy option and contributing to regional development (Noorollahi et al., 2019). It helps countries alleviate their reliance on fossil fuels, given that climate change poses severe uncertainty on energy generation for countries (Guangul

& Chala, 2021). On the other hand, there are various barriers to geothermal energy development, mainly centering on specific subgroups such as technical, political/legal, economic/financial, social/educational and environmental (Taleb, 2009; Bai & Patil, 2014; Sanchez-Alfaro et al., 2015; Shah et al., 2019; Taghizadeh-Hesary, 2020; Puppala et al., 2022). Although each subgroup includes many factors, some correspond to common challenges across most countries.

As discussed in many studies, geothermal energy investments are associated with high exploration risks, significant drilling costs, elevated capital expenditures (CAPEX), prolonged construction periods and extended payback times (Bai & Patil, 2014; Li et al., 2015). The site-specific design of geothermal projects limits economies of scale and equipment standardization. The small size of the geothermal market, combined with limited competition and a small number of manufacturers and service providers, has hindered significant reductions in geothermal investment costs over the past decade (IEA, 2024). Indeed, these structural problems account for geothermal projects' lagging behind other renewables with their rapidly increasing competitiveness, such as wind and solar. When considering global levelized cost of electricity between 2010 and 2023, it increased by 31 % for geothermal, decreased by 90% for solar PV and 70% for onshore wind (IRENA, 2024b). At this point, supporting geothermal projects that already struggle with technical and financial problems becomes vital. Taleb (2009) indicates that the lack of government-led incentives in Saudi Arabia is an essential political barrier to progressing geothermal energy in the country, considering the high upfront capital costs. Providing financial incentives such as capital-investment subsidies or rebates can be critical for increasing the utilization of geothermal in the country. Furthermore, meeting the cost of failed wells in the exploration stage, offering feed-in tariffs for electricity generation and providing tax benefits can support the development of geothermal projects (Sanchez-Alfaro et al., 2015).

In many countries, geothermal energy falls under the mandate of different institutions. Nonetheless, the lack of institutional coordination on geothermal issues complicates the processes from exploration to operation for investors and creates uncertainty in procedures. In addition, the absence of clear and comprehensive

regulations regarding land use and exploration rights makes negotiating between investors, landowners and local communities more challenging (Sanchez-Alfaro et al., 2015). Lengthy approval and permit procedures before drilling operations are other obstacles to geothermal projects (Bai & Patil, 2014) and in many countries, obtaining permits for geothermal projects can require 5-10 years (IEA, 2024). Indeed, the presence of multiple institutions to which investors must apply, along with insufficient information regarding permitting and legal processes, causes many projects to be delayed or failed (Shah et al., 2019). Hence, the integrated and centralized management of geothermal resources is critical for the successful implementation of projects (Pan et al., 2019).

Inadequate technology and R&D activities, a lack of skilled professionals and the absence of industrial standards are major technical barriers to geothermal project development. At this point, the new technologies that will reduce drilling costs can play an essential role, given that the drilling costs account for approximately 40-60% of total project costs (Bai & Patil, 2014). Nonetheless, geothermal projects require more sophisticated machinery by nature and most of the technology is imported from other countries, which makes the operation and maintenance of these types of equipment with current human resources more challenging (Puppala, 2022). Moreover, inadequate R&D studies and investments prevent domestic manufacturing of these technologies (Shah et al., 2019). As another point, it takes many years to specialize a staff generally from geothermal sciences and engineering in geothermal concepts. The operation of complex processes in the field necessitates skilled professionals, so deliberate human resource management (Noorollahi et al., 2019). The lack of industry standards specific to geothermal and generally applying those regarding conventional generation plants also puts a strain on providing energy conservation and emission reduction requirements for geothermal plants (Bai & Patil, 2014).

Another critical barrier to geothermal development is low social acceptance. The literature on this specific theme has flourished rapidly in recent years. There are many studies indicating the low social acceptance of geothermal energy, such as Rosso-Cerón and Kafarov (2015) for Colombia, Pellizzone et al. (2015) for Italy, Liu

et al. (2018) for China, Payera (2018) for Chile and Im et al. (2021) for Korea. Limited public knowledge and environmental awareness, along with resistance to change, are key factors influencing the social acceptability of geothermal energy, as observed in the case of Saudi Arabia (Taleb, 2009). In the study evaluating the barriers to harnessing geothermal energy in India, Puppala et al. (2022) regard the fear of consumer acceptance and lack of knowledge on benefits and drawbacks as social challenges for developing geothermal projects. Indeed, the significance of social acceptance becomes more evident when large-scale projects are realized, as in Pakistan (Shah et al., 2019) and social resistance increases as these projects progress and cause some environmental problems (Yasukawa et al., 2021). Furthermore, the perception of induced seismicity by geothermal drilling, negative impacts on limited water resources and lack of communication between the stakeholders in consultation processes and project development can be other factors triggering the local resistance to geothermal (Dowd et al., 2011). Given that social acceptance is a critical factor in initiating geothermal projects, focusing on reducing unfavourable impacts of geothermal on the locals, providing additional benefits to them and stimulating community engagement can be effective strategies to increase social acceptance (Karytsas & Polyzou, 2021).

Although some studies have examined the opportunities and challenges of geothermal energy in Türkiye, systematic qualitative analyses of stakeholder perspectives remain largely absent. Among these studies, Aksoy (2014) points out resource risks, increasing investment costs, environmental problems caused by emissions and improper reinjection operations in the Turkish geothermal energy sector. Halaçoğlu et al. (2017) highlight the importance of accurate resource data to make reliable assessments in the exploration areas, cooperation between the private sector and academia, offering different incentive mechanisms to investors (feed-in tariff, local manufacturing incentives, tax exemptions, etc.) and funding geothermal projects. Teke and Yaşar (2018) address the urgent need for efficient resource management, effective monitoring and control mechanisms, reduced bureaucracy and measures to prevent environmental pollution. To evaluate the country's potential, Zaim and Çavşi (2018) emphasize providing a national plan for geothermal development, establishing a governmental organization directly responsible for

geothermal projects, the existence of government-supported geothermal plant investments and foundation of R&D centres in the neighbourhood of resource-rich regions. Serpen and DiPippo (2022) attribute the slowdown in geothermal energy investments in Türkiye as of 2021 to the changes in the YEKDEM mechanism and the country's reaching its limit in finding new areas for electricity generation. Furthermore, they stress the importance of increasing public involvement and awareness in realizing a new geothermal project. While insisting on financing the direct utilization of geothermal resources, Şener et al. (2023) stress that regional heating networks should be established in coordination with local authorities to benefit from the country's potential.

Several field-based studies employing surveys and interviews indicate that social acceptance of geothermal energy in Türkiye remains low. At this point, while Cetiner et al. (2016) for Biga, Çanakkale, highlight a lack of sufficient knowledge regarding geothermal energy and its environmental impacts. Ekşi et al. (2019), in the case of Bornova, İzmir, reveal that social acceptance of geothermal energy is lower compared to other renewable sources and that local residents object to the establishment of geothermal facilities in close proximity to their living environments, as widely noted in the Not-In-My-Back-Yard (NIMBY) literature. On the other hand, Tolunay and Erden (2021) report that among the individuals in Denizli, Manisa, Uşak and Aydın, there is a prevailing belief that geothermal energy cannot be regarded as genuinely renewable and does not contribute to regional socio-economic development, but instead poses negative impacts on agricultural activities as well as water and soil resources. Similarly, Tunçbilek and Yılmaz (2022) point out that in Efeler, Aydın, local residents oppose geothermal energy due a range of environmental and socio-technical concerns, including earthquake risk, health impacts, nuisance factors (noise, odor, landscape) and inadequate reinjection practices. However, the study emphasizes that social acceptance could be improved through active engagement of local communities before project initiation, as well as by providing certain benefits and developing geothermal direct-use applications as in the successful example of Afyon.

As shown in Table 4.1, semi-structured interviews and surveys with stakeholders are among the most commonly used methods in the geothermal energy development literature.

Table 4.1. Overview of selected studies on opportunities and challenges of geothermal energy

Study	Country	Main focus	Method	Participants (Sample)
Taleb (2009)	Saudi Arabia	Barriers hindering the utilization of geothermal resources Potential enablers to overcome the barriers	Semi-structured interview analysis	Academics, engineers, geologists, senior managers and energy consultants **(n=19)**
Kubota et al. (2013)	Japan	Significant barriers to the development of geothermal power generation with an emphasis on social acceptance	Semi-structured interview analysis	Developers, hot spring inn managers and local government officials **(n=26)**
Sanchez-Alfaro et al. (2015)	Chile	Perceived advantages, barriers and incentives for geothermal development	Survey analysis	Representatives of government institutions, industry and academia **(n=30)**
Winters & Cawvey (2015)	Indonesia	Governance obstacles to geothermal energy development	Interview analysis	Central government officials, international business consultants, domestic industry insiders, foreign aid agency staff involved with renewable energy development, provincial officials and representatives of the local office of PLN, the national electricity company **(n=26)**
Shortall & Kharrazi (2017)	Iceland and Japan	Influence of cultural characteristics on geothermal energy development	Structured and semi-structured interview analysis	Decision-makers and experts from two countries **(n=8)**
Yasukawa et al. (2021)	Eastern and South-Eastern Asian countries	Environmental barriers to geothermal development	Survey analysis	Geothermal experts, including academia, industry and government
Shah et al. (2019)	Pakistan	Barriers to the adoption of cleaner energy technologies also including geothermal energy	Modified Fuzzy Delphi method Fuzzy Analytical Hierarchy Process	University professors, senior research fellows, board members of the RE institute in Pakistan and investors **(n=14)**
Puppala et al. (2022)	India	Identification and analysis of barriers to harnessing geothermal energy	Fuzzy Delphi method Fuzzy Analytical Hierarchy Process	Researchers working in the domain of geothermal energy in India and scientists **(n=8)**
Taghizadeh-Hesary (2020)	Japan	Analysis of the various barriers to geothermal energy deployment	Vector Error Correction model	Variables proxy for barriers obtained from different data sources
Bai & Patil (2014)	China	Identification of growth barriers to the exploitation of geothermal energy	An overview study	
Setiawan (2014)	Indonesia	Progress, challenges and the prospect of geothermal energy development	Qualitative-descriptive method focused on the literature review	
Noorollahi et al. (2019)	Iran	Geothermal energy development, benefits, challenges and future policy	An overview study	
Guangul & Chala (2021)	Ethiopia	Opportunities and challenges of developing geothermal energy	An overview study	

This study, which also focuses on the opportunities and challenges of geothermal energy development, contributes to the literature by incorporating the experience of

Türkiye, one of the fastest-growing countries in geothermal power capacity since 2015. As the first comprehensive qualitative analysis based on semi-structured interviews conducted in Türkiye, it seeks to identify the current challenges faced by the energy sector and to propose potential solutions. Furthermore, it examines both the current and future opportunities for geothermal energy in a developing country that continues to rely heavily on fossil fuels while pursuing ambitious decarbonisation goals.

4.2. Methodology: Semi-structured Interviews

4.2.1. Research Design and Rationale

Quantitative and qualitative research strategies are widely employed by scholars to explore and address their research questions. These two strategies fundamentally differ from each other in terms of the data acquired in the research process, i.e., quantitative research generates the data in the form of numbers, whereas qualitative one produces it textually (Garbarino & Holland, 2009).

Another important distinction between these two strategies comes from their perspectives of "explanation" and "comprehension" as clarified in the study of Gelo et al. (2008). Quantitative methods aim to explain, i.e., to assess whether the observed phenomena and their systematic relationships align with the predictions of a theory. On the other hand, qualitative methods focus on increasing comprehension along with personal perspectives, experiences and understandings of the individual actors. Indeed, the quantitative approach is driven by a theory and aims to test existing hypotheses as a confirmatory study, whereas a qualitative one focuses on developing a theory based on observations from the exploratory study and the formulation of the hypothesis is an integral part of the research process itself.

For the data collection process, quantitative approaches use experiments, questionnaires, structured interviews, official documents, whereas qualitative ones gather data from open-ended (semi-structured) interviews, focus group interviews, observations, official and personal documents. While quantitative studies employ

usually systematic (random) sampling and require usually a large sample size for statistical analyses, qualitative research can focus on a small sample chosen in an opportunistic or goal-driven manner (Gerring, 2017). Quantitative methods encompass the processes of collection, analysis, interpretation and writing the results of a study. On the other hand, qualitative research usually uses purposive sampling, common strategies include gathering open-ended data, analysing text or pictures, presenting information in figures and tables and offering personal interpretation of the findings (Creswell, 2009). These purposive sampling techniques include convenience sampling (i.e. selection of units easiest to access), homogeneous cases sampling (i.e. choosing units from a subgroup to study in detail), snowball sampling (i.e. using informants for the addition of useful and relevant elements into the sample) or extreme, deviant and typical case sampling (i.e. involvement of specifically the most prominent cases in the sample to get information as much as possible about the outliers or the most representative ones from the subpopulation) (Gelo et al., 2008).

Applying semi-structured interviews is a common data collection method in qualitative data analysis. The overall purpose of this method is to gather information from individuals with enough knowledge and personal experience on the topic of interest. It allows the researchers to gain an insight into how much their prior information on a specific issue coincides with the behaviour and perceptions of significant actors in the research area (Horton et al., 2004). In this research design, the interviewees face a pre-determined set of open-ended questions. Different than the structured one relying on a fixed set of questions in a specific order, a semi-structured interview is not restricted to these questions; it can be expanded through further discussion. At any moment, the participants can offer new research questions to enthusiastic researchers. In this way, semi-structured interviews offer greater flexibility to gather comprehensive, engaging and relevant information from the respondents following the natural flow of the interview (Barriball & While, 1994).

This study adopts a qualitative research strategy to examine the opportunities and challenges of geothermal energy development in Türkiye. In the previous chapter, the Turkish Geothermal TIS was analysed using official documents, reports and

market data. Although these secondary sources provide valuable insights into the sector's evolution, their formal and standardized format often limits a deeper understanding of stakeholders' genuine perspectives and concerns. To address this limitation, the study employs semi-structured interviews as a complementary data collection method given that the triangulation of multiple data sources helps to minimize potential biases and enhance the overall validity and reliability of the research (Morgan, 2022). Through these interviews, the study aims to capture diverse viewpoints, identify key issues and explore areas of consensus and disagreement among stakeholders, while also uncovering the factors that have influenced-and are likely to influence- the diffusion of geothermal energy in Türkiye.

4.2.2. Participant Selection and Sampling Strategy

The purposeful sampling method, frequently used in qualitative research, focuses on identifying and selecting individuals who are particularly well-informed about or experienced with the issue being addressed (Creswell & Plano Clark, 2011). This selection can be made by contacting people in touch with the key individuals in the specific area. As a main advantage of this method, it allows for the collection of a broad perspective in the research area from leading individuals (Suri, 2011), who are assumed to represent the views of the majority. Furthermore, there is no specific restriction on the sample size as long as the intended information is acquired (Tongco, 2007). However, a bias could occur, such as not getting the view from less represented stakeholders. At this point, snowball sampling can be helpful. Snowball sampling is a method in which participants are asked to propose other potential interviewees, enabling the researcher to exert minimum time, money and effort (Cohen & Arieli, 2011). Also, this method allows for a more diverse and inclusive participant pool to interview, which is crucial for obtaining the view of the whole. The snowballing method is used after contacting the leading stakeholders by purposeful sampling and other stakeholders are obtained from the initial list. With the snowballing technique, at first, there will be many new names; however, as the interviews progress, this list converges to a final one (Suri, 2011). This method can help reduce the bias and gather the views of the underrepresented stakeholders.

To identify the opportunities and challenges for geothermal energy development in Türkiye, semi-structured interviews with 21 participants were conducted for this study between December 2021 and January 2023. This period was particularly important as it coincided with significant changes in the YEKDEM support scheme. Before selecting the final interviewees, the key stakeholder groups in the Turkish geothermal sector were initially identified through a literature review based on their different roles, interests and levels of influence. These groups, which can affect or be affected by the success of geothermal projects, mainly included financial institutions, manufacturers, plant operators, municipalities, central and local government authorities, landowners, local communities (e.g., residents and farmers), customers (e.g., heat users and hot spring operators), academia, and non-governmental organizations, drawing on prominent studies such as Shortall et al. (2015), Climo et al. (2016), and Yasukawa et al. (2018). Accordingly, for the purposes of this study, 56 stakeholders from six stakeholder groups were initially identified through stakeholder mapping based on a power–interest analysis. The purpose of this mapping was to identify the relevant stakeholder universe as the basis for selecting the final interviewees.

As a stakeholder mapping method, the power-interest matrix provides the categorization of the stakeholders according to how much influence they have and how interested they are in supporting or opposing a particular strategy (Johnson et al., 2008). As illustrated in Figure 4.1, the four quadrants of this matrix correspond to four categories of stakeholders. As clarified in the studies of Johnson et al. (2008), Ackermann and Eden (2011) and Jolanta (2015), these stakeholders with different interests and power levels require different strategies. The stakeholders with high interest and high power are the key players that need to be engaged and managed regularly. The stakeholders with low interest, but high power are the ones that should be kept satisfied since they can only stay passive until their interest level changes. On the other hand, the stakeholders with low power, but high interest are the ones who should be informed since they may have the power of influencing others. Finally, the stakeholders with low interest and low power are the ones requiring minimum effort, but that should be monitored in case of any changes in their interest or power.

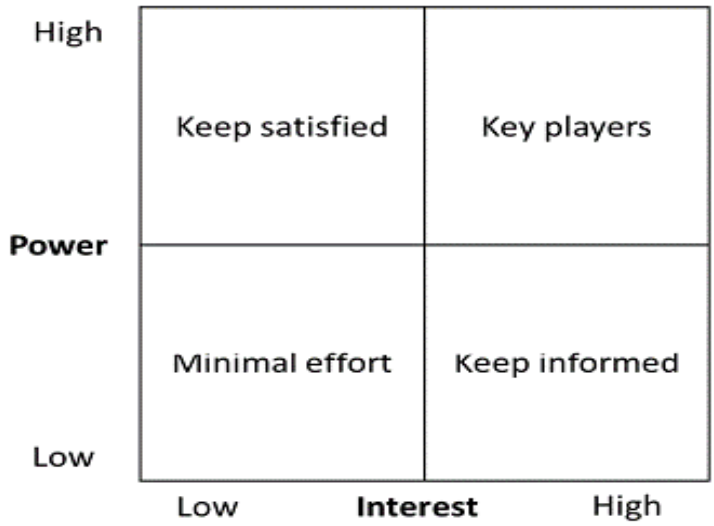

Figure 4.1. Power-Interest matrix

As part of the stakeholder mapping process of this study, 56 stakeholders in the Turkish geothermal sector were first identified and then ranked according to their levels of power and interest. They were valued on a scale of 0-2, with 0 meaning low level and 2 meaning the highest level. Then, they were mapped on the Power-Interest matrix illustrated in Figure 4.2 to identify which ones are more relevant and essential for the study. While the term "power" is defined in this study as the "power of the stakeholder to influence the sectoral development", the term "interest" refers to the "impact of sectoral development on the stakeholder." The individuals with a high level of power and interest were the target interviewees of this study. Indeed, those marked by green in Figure 4.2 were in the final interviewee list.

Based on the stakeholder mapping and the power-interest analysis, fifteen stakeholders were initially selected through purposive sampling for the interviews. Subsequently, six additional participants were recruited through snowball sampling. The snowball sampling approach was particularly appropriate for this research because stakeholders in the Turkish geothermal sector are closely connected and were therefore able to recommend other individuals with relevant expertise and experience. As a result, a total of 21 respondents representing diverse stakeholder groups participated in the interviews. The final sample size was considered appropriate, as all major stakeholder groups relevant to the Turkish geothermal sector were represented with an adequate number of participants. Furthermore, the

later interviews largely reinforced the views and issues identified in earlier interviews, indicating that the data collected adequately addressed the objectives of the study.

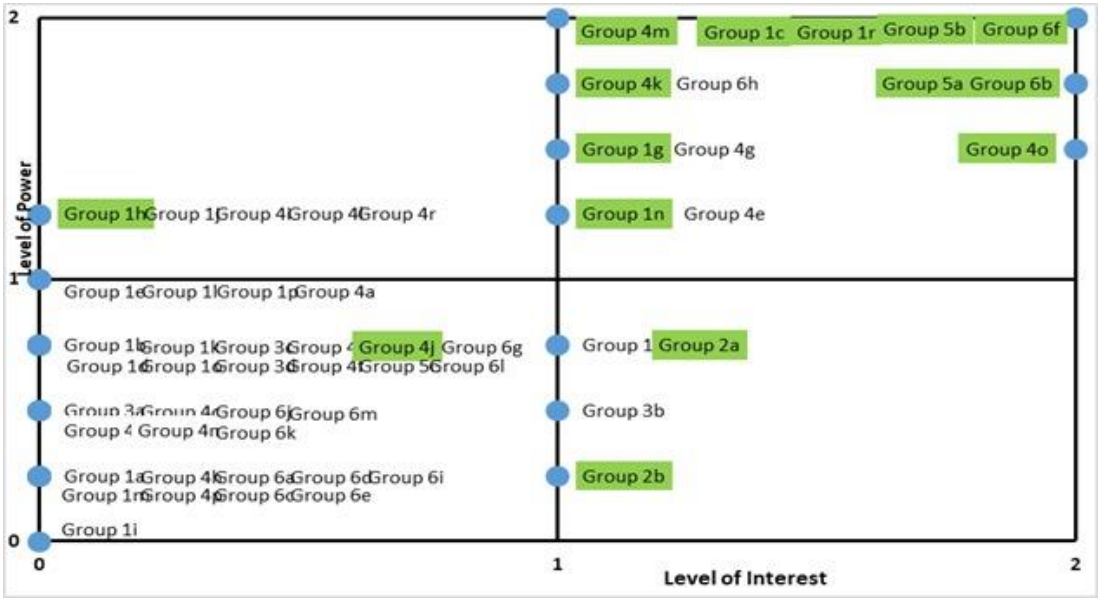

Figure 4.2. Power-Interest matrix of stakeholders in the Turkish geothermal sector

Group 1: Ultimate end users; **Group 2:** Optional end users; **Group 3:** Manufacturers; **Group 4:** Primary influential bodies; **Group 5:** Investors and financial Institutions; **Group 6:** Academia and policymakers

4.2.3. Conducting the Interviews

Before finalizing the interview questions, a preliminary set of questions was first developed. Subsequently, an online pre-meeting was held with participants from various sectors, including academicians, researchers, plant operators and banking sector officials. During this meeting, the interview questions were assessed for validity and relevance. Based on the feedback, the initial questions were revised, leading to the finalization of the interview question list.

These interviews were conducted as part of a policy-oriented work package within a technical geothermal project; therefore, the interview document also included several project-specific technical questions (GeoSmart innovations). Thus, the final question list comprised eighteen questions, five of which focused on geothermal innovation from the perspectives of plant operators and investors. For the purposes of this study,

the thirteen main questions used are presented in Appendix A.1. Through the interview questions, it is aimed to reveal the interviewees' opinions on the Turkish geothermal sector, the role of geothermal energy in energy mix policies, the opportunities it offers, the challenges hindering its further development in the country and related policy recommendations. Furthermore, social acceptance of geothermal energy was one of the issues addressed during the interviews.

Table 4.2. Interviewee groups

Interviewee groups	**# of respondents**
Group 1: Ultimate end users and beneficiaries, including	4
Group 2: Optional end users, mainly R&D companies	4
Group 3: Influential primary bodies: public mineral research and exploration institution, geothermal energy associations, or governorships	5
Group 4: Investment enterprises, banks, or regional development agencies	3
Group 5: Academia and public policymakers	5
Total # of respondents	**21**

The interviews were conducted with 21 participants from five stakeholder groups representing the Turkish geothermal energy sector, as presented in Table 4.2. Even though the unavailability of some groups, such as manufacturers or local people, seems to offer a certain amount of selection bias to the research, a participant from a leading NGO was included as the representative of local people and those from R&D companies as those of manufacturers.

The interview document encompassing the potential questions was sent to the participants in advance by e-mail to familiarize them with the questions. Interviews were scheduled based on participants' availability, conducted online and lasted between 60 and 90 minutes. At the beginning of the interviews, participants were clearly informed that all data collected from the interviews would be handled with strict confidentiality and anonymity. Similarly, all interviews were recorded with the interviewee's consent for transcription and subsequent analysis. All procedure for conducting semi-structured interviews are summarized in Figure 4.3.

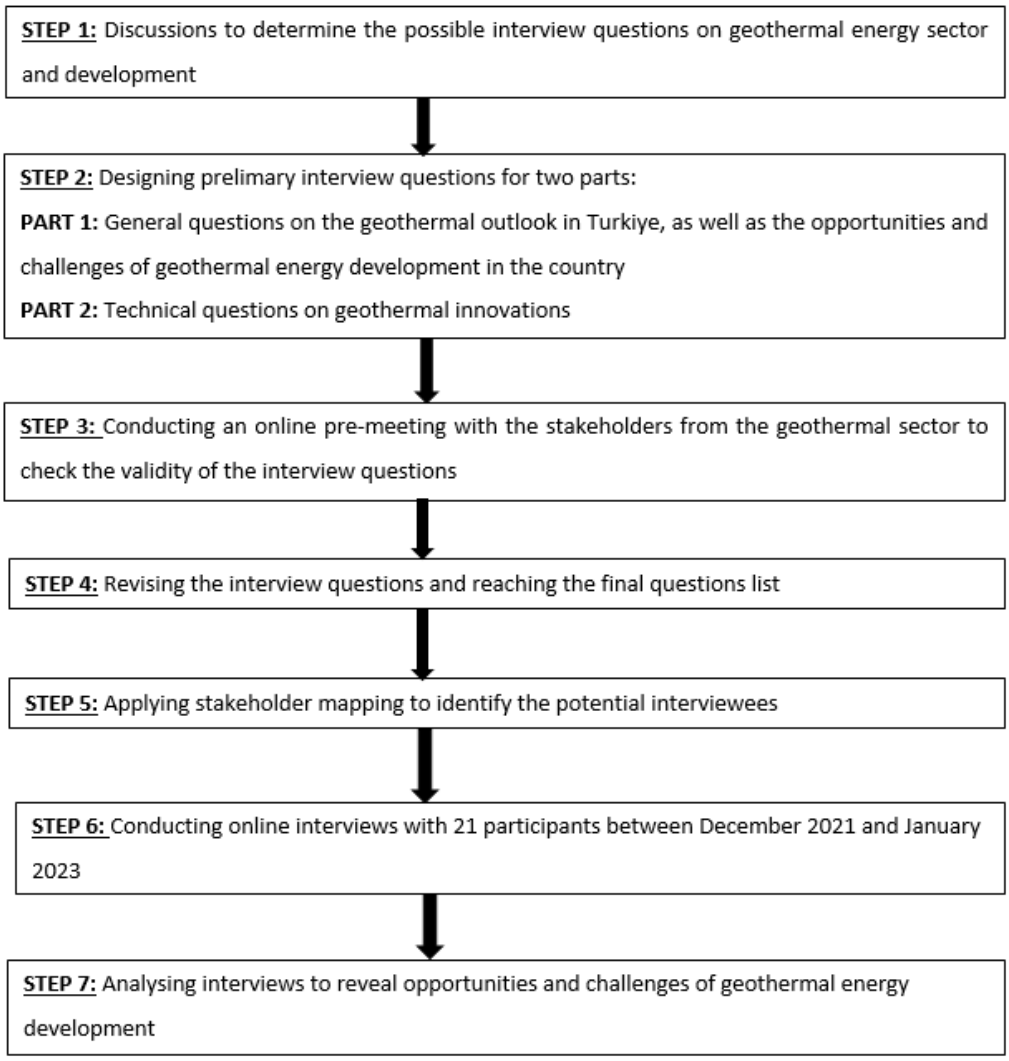

Figure 4.3. Procedure for conducting semi-structured interviews

Source: Adapted from Meirbekova et al. (2024)

Table 4.3 presents the background information on the interviewees listed in Table 4.2. All participants possessed strong educational and technical backgrounds, with most having over ten years of experience in the energy sector. Some participants had prior field experience or were still actively working in the field, providing valuable insights for this study. Out of 21 interviewees, 14 were male and 7 were female, indicating a gender inequality that reflects the male-dominated nature of the geothermal sector. As a limitation of the study, aside from one NGO manager, the interviewees did not represent societal stakeholders. Therefore, further research could be conducted, particularly focusing on social acceptability at the community level, which was not addressed in this study.

Table 4.3. Information on interviewees

ID	Gender	Background	Years of experience	Current employment	Group ID
1	Male	Social Science	19	Manager in the energy company	Group 1
2	Male	Engineering	26	Manager in the geothermal energy company	Group 1
3	Male	Social Science	34	Manager in the geothermal energy company	Group 1
4	Male	Engineering	7	Manager in the geothermal energy company	Group 1
5	Male	Engineering	10	R&D manager in the geothermal energy company	Group 2
6	Male	Engineering	35	Founder of the R&D energy company	Group 2
7	Male	Engineering	36	Engineer in the R&D company	Group 2
8	Female	Engineering	15	Founder of the energy consulting company	Group 2
9	Female	Social Science	17	Manager of the non-governmental energy organization	Group 3
10	Male	Engineering	27	Manager in the energy sector	Group 3
11	Male	Engineering	11	Expert in the energy sector	Group 3
12	Male	Economics	32	Manager in the geothermal energy association	Group 3
13	Male	Engineering	15	Manager in the governorship	Group 3
14	Female	Engineering	16	Expert in the bank	Group 4
15	Female	Social Science	21	Manager in the bank	Group 4
16	Female	Social Science	8	Expert in the regional development agency	Group 4
17	Male	Engineering	13	Manager in the energy sector	Group 5
18	Male	Engineering	30	Academician	Group 5
19	Female	Engineering	19	Academician	Group 5
20	Female	Engineering	16	Manager in the energy sector	Group 5
21	Male	Engineering	40	Mayor at present	Group 5

4.2.4. Interview Data Analysis

In qualitative research, thematic analysis and content analysis are two widely used data analysis approaches. While thematic analysis is a method for identifying, analysing and reporting patterns (themes) within data (Braun & Clarke, 2006, p. 79) and particularly focuses on interpreting both explicit and implicit (latent) meanings (Namey et al., 2008), content analysis aims to identify patterns and trends in language use, including word frequency, relationships and the structures and discourses of communication (Vaismoradi et al., 2013, p. 400). In comparison to content analysis, which focuses primarily on the numerical description of textual

data, thematic analysis involves a higher level of researcher engagement, moving from description to interpretation and requiring greater intellectual contribution (Staller, 2015). While both approaches have their respective strengths and weaknesses, the choice between them depends on their suitability to the research topic and the extent to which systematic analytical procedures are followed (Özden, 2024).

For qualitative data analysis, coding the textual material (i.e., transcriptions, memos and field notes) is a commonly applied analytical approach, serving as an intermediate step between data collection and interpretation. In this process clarified in the study of Gelo et al. (2008), the researchers first divide the texts into the units such as sentences, phrases or passages and then label them. By considering the similarities and differences among these labelled text units, they are systematically grouped into themes or content categories. This process enables a more structured representation of the data and facilitates the identification of key components within the analysed texts. On the other hand, a coding framework in qualitative research can be developed using a deductive approach, an inductive approach, or a combination of both. In deductive coding, researchers usually construct their initial codes from existing theories, literature and research questions, whereas inductive coding relies on the analytic process itself, allowing codes to arise from the data rather than being predetermined (Azungah, 2018). In the inductive approach, codes are generated from the raw data through the identification of recurring, prominent, or significant themes (Thomas, 2003).

In this study, thematic analysis is adopted to facilitate the identification and interpretation of key themes within the interview data, while also exploring underlying meanings and capturing participants' experiences and perspectives. Firstly, a coding scheme was deductively developed based on the literature review and research objectives, then it was iteratively refined through inductive approach to capture themes emerging from the interview data. To ensure a systematic approach to the complex coding process, MAXQDA 2022 was employed in this research as the qualitative data analysis tool. The MAXQDA affords researchers notable flexibility in structuring and categorizing qualitative data, which not only facilitates the coding

process but also supports the ongoing refinement of codes during analysis (Marjaei et al., 2019).

Utilizing the coding tool proposed by MAXQDA, the most cited issues on geothermal energy during the interviews were identified as opportunities and challenges. The opportunities were also classified as “current” and “future”, while the challenges were grouped under four categories: “political/regulatory/institutional”, “financial/economic”, “technical” and “environmental/social”, in align with the similar studies in the literature. Besides these main coding categories, several sub-codes were also developed under each category to better understand the different aspects of the interview data. Accordingly, each statement of the participants was matched with the relevant coding item and coding frequencies were obtained for each item and coding category.

It is important to note that the main rationale for analysing coding frequencies and percentages in this study was to obtain a clearer understanding of the themes most frequently emphasized by the interviewees, rather than to impose a strictly numerical interpretation of the data, as is typical in content analysis.

4.3. Interview Results: Opportunities and Challenges for Development of Geothermal Energy in Türkiye

During the interviews, participants identified a range of opportunities and challenges in evaluating the development of the Turkish geothermal energy sector. They emphasized both the current advantages of geothermal resources and their future potential for Türkiye. At the same time, they expressed concerns regarding political, financial, environmental and social challenges affecting geothermal energy expansion. In particular, they highlighted financial difficulties faced by plant operators and pointed to existing political and regulatory barriers. They also raised social and environmental concerns related to improper practices. As illustrated in Table 4.4, although the interviewees provided predominantly negative assessments of the current state of the geothermal energy sector, they remained generally optimistic about its future.

Table 4.4. MAXQDA output on the opinions on opportunities and challenges

Code System	Positive(today)	Negative(today)	Hopeful(future)	Hopeless(future)	SUM
Opportunities					0
Current	57	14	59	1	131
Future	22	27	31	3	83
Challenges					0
Political/Regulatory/Institutional	4	34	10	6	54
Financial/Economic	13	48	15	25	101
Technical	3	20	5	2	30
Environmental/ Social	13	24	10	2	49
SUM	112	167	130	39	448

The participants who regarded financial barriers as the most crucial today were also hopeless about the future. Concentrating on group-based opinions presented in Table 4.5, it is evident that plant operators and participants from R&D companies were the most pessimistic about the current state of geothermal energy, while academicians and policymakers were the most optimistic about its future prospects.

Table 4.5. MAXQDA output on group-based general opinions on geothermal energy

Code System	Group 1	Group 2	Group 3	Group 4	Group 5	SUM
Opinions						0
Positive(today)	15	13	8	8	16	60
Negative(today)	26	24	19	9	17	95
Hopeful(future)	13	12	13	6	22	66
Hopeless(future)	10	7	1		2	20
SUM	64	56	41	23	57	241

Group 1: Ultimate end users and beneficiaries; **Group 2:** Optional end-users; **Group 3**: Influential primary bodies; **Group 4:** Investors and financial institutions; **Group 5:** Academia and policymakers

Commenting on both tables together, the findings reveal a clear distinction between short-term and long-term perceptions. While stakeholders generally viewed the current state of the geothermal sector more negatively than positively, most remained optimistic about its future. This pattern suggests that the relatively pessimistic assessment of the current state of the sector is associated primarily with the existing political, regulatory, financial, technical and environmental challenges, rather than with doubts about the long-term potential of geothermal energy itself.

4.3.1. Challenges

The respondents, pointing out the geothermal energy potential in the country during the interviews, concentrated on the challenges of its exploitation and development. Among these challenges, financial and economic ones were the most stressed. Furthermore, while indicating the political, regulatory and institutional barriers, they highlighted the environmental and social problems. Compared to the group-based opinions in Table 4.6, the plant operators centred on all challenge categories. On the other hand, the participants from R&D companies, academicians and policymakers were concerned primarily about financial and economic challenges, while primary bodies and investment enterprises were about environmental and social ones.

Table 4.6. MAXQDA output on group-based opinions on opportunities and challenges

Code System	Group 1	Group 2	Group 3	Group 4	Group 5	SUM
Opportunities						0
Current	61	57	44	41	94	297
Future	52	25	51	17	44	189
Challenges						0
Political/Regulatory/Institutional	60	14	23	17	21	135
Financial/Economic	50	27	26	16	26	145
Technical	25	10	11	8	17	71
Environmental/ Social	46	9	34	22	16	127
SUM	294	142	189	121	218	964

Group 1: Ultimate end users and beneficiaries; **Group 2:** Optional end-users; **Group 3:** Influential primary bodies; **Group 4:** Investors and financial Institutions; **Group 5:** Academia and policymakers

Most barriers underlined by stakeholders in Table 4.7 as hindering the diffusion of geothermal energy in Türkiye are similar to those encountered in many other countries. To illustrate, the study by Meirbekova et al. (2024) focusing on the challenges of geothermal energy development in three European countries such as Belgium, Iceland and Italy through stakeholder interviews[7] offers important inferences. In these interviews, some challenges for the development of geothermal energy are identified as follows: a complex and lengthy authorization process and limited public awareness, lack of incentives supporting innovative plants and

[7] These interviews were conducted simultaneously in Türkiye, Belgium, Iceland and Italy within the scope of GeoSmart Project with same interview questions.

schemes for geothermal risk mitigation in Italy; the need for technological solutions and inconsistent political support in Belgium; sustainable resource exploitation and some technical issues such as silica scaling in Iceland.

Table 4.7. Challenges hindering the development of geothermal energy in Türkiye[8]

Codes	Frequency	Percentage (%)
Challenges	**478**	**49.6**
Political/Regulatory/Institutional	**135**	**28.2**
Lack of institutional coordination/lengthy approval process, etc.	18	13.3
Competition to natural gas, regional lobby activities	6	4.4
Poorly development of direct utilization areas	26	19.3
Legislative gaps	21	15.6
Fragmented market (small, non-institutional, domestic firms)	27	20
Conflicts between investors, land owners, or municipality	14	10.4
Inadequate monitoring and auditing	23	17
Financial/Economic	**145**	**30.3**
Lack of direct utilization incentives	25	17.2
Current economic conjuncture	14	9.7
Current incentive scheme (for a particular time, in TRY)	34	23.4
Foreign dependency on technology	10	6.9
Investor costs (drilling, risks, long payback period, etc.)	62	42.8
Technical	**71**	**14.9**
Same reservoir use/reservoir management problems	14	19.7
Demand for further information/R&D/technology	19	26.8
Plant installation above resource capacity by ignoring efficiency	14	19.7
Technical deficiencies (fluid quality, silica, cooling problems)	17	23.9
Inadequate geothermal standards	7	9.9
Environmental/ Social	**127**	**26.6**
Profit-oriented investor attitude	30	23.6
Poor social acceptance/local resistance	53	41.7
Misperception/insufficient information among the public	21	16.5
Smell/improper reinjection practices	23	18.1

Although many of these highlighted barriers for these countries are relevant to the Turkish case, it is interesting that Turkish interviewees also linked geothermal-related environmental and social problems to the market's fragmented structure. Furthermore, while criticizing the recent changes in the YEKDEM mechanism, they also acknowledged that these incentives acted as a driving force for investments

[8] "Frequency" corresponds to how many times the respondents mentioned the related item during the interviews as a challenge to geothermal projects, and "Percentage" indicates the share of this item in the corresponding challenge subgroup. Frequencies and percentages for sub-codes are calculated within each main category. The same interpretation applies to the opportunity part.

driven by profit motives, often exceeding resource capacity. The participants, who frequently emphasized the country's potential, were insistent on formulating policies to promote direct utilization of geothermal energy and provide incentives to investors.

4.3.1.1. Political, Regulatory and Institutional Challenges

As many interviewees stated, the Turkish geothermal energy market evolved as a fragmented sector, accounting for many problems today. The geothermal energy investments in the country were remarkably on the rise after 2010, along with increasing financial incentives offered to the power plants under the YEKDEM mechanism. As a result, the geothermal energy market became very attractive for investors at that time, even those from non-energy sectors such as construction, textile and real estate. While the geothermal power sector experienced significant momentum with the entry of each new player, the penetration of these small, non-institutional and primarily domestic firms into the market also brought about some structural problems. The improper practices of these firms with only profit-oriented attitudes fired up the local resistance, which also caused dissatisfaction among the large and institutional companies in the sector over time. Ultimately, these displeased companies resorted to establishing another geothermal energy association by departing from the national one. At this point, the comment of one of the interviewees (#1) was quite striking: "*The most complicated renewable energy sector was left in the hands of small and non-cooperate firms. It is the most important problem in the country's geothermal energy story*."

Offering incentives only to power plants was another issue strongly criticized by the interviewees. The lack of an additional mechanism to incentivize direct utilization practices was frequently highlighted as the most critical obstacle to realizing the country's full potential. Indeed, Italy's geothermal story, from pioneering the world's first geothermal power plant to experiencing a significant slowdown in development over time, parallels the challenges encountered by Türkiye. Lengthy and uncertain authorization processes, coupled with limited support schemes for power generation and the absence of such support for direct utilization, stand out as the main factors

hindering geothermal energy development in Italy (Manzella et al., 2019). Besides one interviewee (#8) advocating that every geothermal energy project should be integrated with a direct utilization application, another participant (#9), a plant operator, stated: "*If additional incentives were offered, I would be willing to undertake such integrated geothermal energy projects, as would many firms in the sector."*

In Türkiye, the involvement of numerous ministries, general directorates and public institutions in geothermal energy-related procedures and issues, together with insufficient inter-institutional coordination and regulatory complexity, results in extended opinion-formulation, decision-making and administrative approval processes, which may discourage investors (Akkuş & Alan, 2016). Similarly, interviewees complained that the country needs centralized management of geothermal energy. From exploration to operation, lengthy permission and approval processes wait for the investors and they should always apply to different institutions to complete all these bureaucratic procedures. One of the interviewees (#18) stated, "*There is no single owner of geothermal energy. Many institutions are interested in the resource. There is a multi-headed system*." the other (#2) complained that "*We are going through such long and exhaustive processes and we are ultimately left alone as investors."* At this point, some participants proposed the establishment of a "Department of Geothermal Resources" within the MENR, either as an independent department or under the General Directorate of Renewable Energy. Lastly, although Provincial Special Administrations or YİKOBs are primarily responsible for conducting inspection activities in their respective regions, they often rely on MTA for technical support due to a lack of qualified and experienced staff (Akkuş & Alan, 2016). Furthermore, interviewees indicated that improper practices by plant operators stemmed from inadequate monitoring and auditing. They argued that legislative gaps in the monitoring mechanisms have led to environmental and social problems over time and continue to do so.

4.3.1.2. Financial and Economic Challenges

During the interviews, one of the most frequently raised issues was the investors' costs. Respondents, particularly those experienced in fieldwork, indicated that

drilling remains a technically complex and costly component of geothermal projects, even with current technologies. They stated that the risks borne by investors are relatively high, given the possibility of failing to reach a resource with the expected enthalpy, or any resource at all, by the end of drilling. However, Serpen and DiPippo (2022) point out that the robust drilling industry in Türkiye is characterized by competition between private and public companies, with drilling prices generally remaining stable. Similarly, Gul and Aslanoglu (2018) in their cost analysis reveal that geothermal well costs in Türkiye are the lowest compared to many other countries such as Australia, France, Germany, Iceland, Kenya, the Netherlands and the United States. This is mainly due to lower rig operation, service and labor costs; the use of low-cost casings since wells are not overbalanced; and Türkiye's extensive drilling experience, which has created a competitive market and reduced drilling times. On the other hand, there are also successful examples of countries, such as France and the Netherlands, that offer national risk mitigation schemes primarily for the drilling of geothermal heating applications. Since the 1980s, France has established short- and long-term funds to promote the country's expansion of geothermal energy usage.[9] At this point, interviewees from investment enterprises emphasized that, although not provided at the national level, geothermal projects in Türkiye benefit from partial drilling subsidies through international funds. These subsidies cover approximately 40% to 60% of well costs in cases of unsuccessful drilling.

The interviewees underlined that geothermal is still less cost-effective than solar and wind energy. The geothermal energy projects with high initial capital costs have more extended payback periods than the other REs, urging investors to consider less expensive alternatives.

Another issue strongly criticized during the interviews was the new YEKDEM scheme, which stipulates that plants commissioned after 2021 are entitled to incentives denominated in Turkish Lira rather than USD. Some interviewees argued that this approach could pose a significant obstacle to new investments, given the

[9] Retrieved January 20, 2024, from https://eurogeologists.eu/european-geologist-journal-43-boissavy-the-successful-geothermal-risk-mitigation-system-in-france-from-1980-to-2015/

depreciation of the domestic currency and the relatively high costs of geothermal energy investments. Indeed, one of the participants (#12) commented on this issue:

> The energy sector, which gained momentum with the initial YEKDEM scheme, entered a period of stagnation under the new TRY-based mechanism, leading to a marked decline in investments after 2021. As YEKDEM is a prerequisite for investment, the mechanism should be urgently revised considering international and financial conditions.

By contrast, some policymakers argued that electricity market prices are now so high that the role of YEKDEM and thus the need to incentivize certain plants in this manner, is increasingly questionable. While some interviewees attributed the sector's recent slowdown to changes in the YEKDEM scheme, others emphasized that the extensive utilization of resources in the Menderes Graben has increasingly constrained the development of new geothermal fields. In this regard, they stressed the necessity of support mechanisms to encourage investors to undertake geothermal exploration in other regions.

Another issue frequently raised was the need to provide financial incentives for direct utilization applications in order to unlock the country's full potential. In this context, several countries stand out as compelling examples of effectively utilizing their geothermal resources. Notably, Iceland meets 90% of its space heating demand through geothermal energy, while in Sweden, 40% of buildings are heated using geothermal heat pumps (Lund & Toth, 2021). One interviewee (#10), emphasizing Türkiye's potential, stated:

> You can benefit from a geothermal resource in multiple ways until you send it back underground. You can generate electricity, heat a house or a greenhouse, operate a thermal facility and then reinject it based on the temperature. The value of these practices has not been widely appreciated in our country. Incentivizing investors for direct utilization is important for both enhancing the understanding of geothermal energy and maximizing its socioeconomic benefits.

4.3.1.3. Technical Challenges

Among the technical barriers hindering geothermal energy development in Türkiye, the participants primarily emphasized the need for further knowledge and

technological advancement. While indicating some problems affecting the power plant efficiency, such as silica precipitation and cooling in summer, they underlined the importance of stronger collaboration between scientific disciplines and the private sector to deal with technical deficiencies and conduct R&D projects. At this point, interviewee (#16) stated: "*A closer linkage is needed between technology developers and end users. The project's sustainability is compromised when the technology providers that offered support during its development phase withdraw once the project is implemented*."

Interviewees strongly criticized that, in the early years of YEKDEM, investors rushed to secure incentives and established plants beyond resource capacity, often disregarding efficiency as well as social and environmental impacts. Furthermore, they complained that the overexploitation of geothermal resources has led to decreased power output over time due to declines in temperature and pressure. One of the interviewees (#8) remarked:

> Geothermal land license areas in Türkiye were not determined based on the reservoir; on the contrary, all divisions were made over the land. In this case, neighbouring power plants had to use the same reservoir. Considering the profit maximization motivation of the investors, the aggressive exploitation of reservoirs now threatens the sustainability of the resource.

In Law No. 5686, geothermal resources are treated similarly to minerals rather than as integrated fluid systems, in contrast to the reservoir-based approach used in oil and gas regulation, which emphasizes coordinated production to maintain optimal reservoir conditions (Pedrosa et al., 2026). In this context, most participants emphasized the need for integrated reservoir management among geothermal developers utilizing the same resource in order to optimize overall field performance and sustain maximum production capacity.

Lastly, they expressed that the technical standards for drilling or the types of equipment utilized in the plants were inadequate. They also disapproved of using some environmental standards specific to conventional energy sources for geothermal energy.

4.3.1.4. Environmental and Social Challenges

Interviewees largely associated the environmental and social problems related to geothermal energy with improper practices by small, non-institutional firms that rapidly entered the market following the introduction of YEKDEM. The design of YEKDEM, which primarily aimed to attract investors into geothermal power generation without sufficiently incorporating environmental considerations, contributed to low levels of social acceptance among local communities. With their only profit-oriented attitudes, these firms demonstrated little or no environmental awareness and largely ignored social acceptance and local resistance. Improper reinjection practices damaging farmers' fields and disturbing smell problems are some factors accounting for low social acceptance of geothermal in the country. Indeed, before Law in 2007 and in the early times when only a limited number of projects were implemented, the remaining geothermal fluids after the power generation process were partially released to nearby streams or agricultural lands (Serpen & DiPippo, 2022). This past misapplication has not been erased from the memory of the local people, which still triggers local resistance to geothermal today. Indeed, Doğdu and Çelmen (2023) highlight that a well-conducted reinjection process brings several advantages. These include ensuring long-term resource sustainability by maintaining reservoir pressure and temperature, facilitating continuous and reliable geothermal power production and improving groundwater quality.

One of the interviewees (#10) stated that the smell problem resulting from the release of hydrogen sulphide severely disturbed the local communities and emphasized:

> The rotten egg smell caused by hydrogen sulphide is a big problem for the local people. Investors trying to convince the public about their projects need to focus more on somehow eliminating or reducing this smell problem that profoundly affects the daily lives of the locals.

In this regard, Iceland provides a good example of subsurface CO_2 and H_2S injection to mitigate the negative impacts associated with resource utilization; therefore, similar disposal systems could also be designed for the Turkish context (TÜBA, 2020).

Many participants highlighted the need for greater public awareness and pointed to widespread misconceptions about geothermal energy. At this point, the interviewee (#10) provided a striking example: "*Water vapour comes out of the geothermal plant. People see it whenever they drive through there and they say, "You see, geothermal energy is spreading the poison out*." Similarly, interviewee (#7) stated: "*There are even some local residents who strongly believe that geothermal energy causes cancer*."

Contrary to the provisions of Law No. 5346, natural gas infrastructure has been extended to many provinces and districts with known geothermal resources and this process continues today (Durak, 2025). At this point, some respondents indicated that natural gas lobbyists have deliberately fostered the prejudice against geothermal energy, thereby fuelling public concerns and social opposition.

Finally, the participants argued that local resistance and low social acceptance problems could only be overcome if the public benefited more from geothermal along with increasing local employment and social responsibility projects and their awareness of the resource can be enhanced starting from schools and extending from families to the wider community. While highlighting regional differences in social acceptance, one of the interviewees (#20) remarked:

> For instance, in the Afyon Sandıklı region with its enhanced geothermal district heating systems and many thermal tourism facilities, we observe a high level of satisfaction among local communities regarding geothermal energy. However, the situation is the opposite in the Aydın Efeler region, where the interaction of geothermal companies with the public is very low. We believe that this difference is fundamentally related to the level of economic benefits geothermal resources provide to the public. Integrated systems with district heating, greenhouse heating and agricultural drying play a crucial role in social acceptance. We have directly experienced that when the public perceives a benefit for themselves, they do not oppose geothermal energy.

4.3.2. Opportunities

Through the interviews, participants frequently highlighted the country's resource potential. They also emphasized future opportunities while outlining the current advantages of having geothermal resources, as presented in Table 4.8.

As illustrated in Table 4.6, academicians and policymakers were the ones who most concentrated on the current benefits of geothermal energy. In this group, policymakers emphasized the importance of geothermal energy in the country's energy mix and security of energy supply. On the other hand, plant operators, primary influential bodies, academicians and policymakers were the primary ones centred on the future opportunities geothermal resources would offer.

Table 4.8. Current and future opportunities for the development of geothermal energy in Türkiye

Codes	Frequency	Percentage (%)
Opportunities	**486**	**50.4**
Current	**297**	**61.1**
Environmentally friendly/sustainable energy source	12	4
More efficient than other REs	11	3.7
Benefits offered by direct utilization	34	11.4
Suitability for direct utilization	38	12.8
Suitability for hybrid energy systems	15	5.1
Increased employment opportunities for locals	16	5.4
The non-intermittent energy source (base load)	13	4.4
Existing human resources and know-how	15	5.1
Paris Climate Agreement requirements/emission reduction	29	9.8
Technological advances	34	11.4
Resource potential in the country	38	12.8
Advantages offered to investors (financing/technical support)	12	4
Being a domestic energy source	11	3.7
High imported energy prices/geothermal use for heating	19	6.4
Future	**189**	**38.9**
Conducting/supporting R&D	32	16.9
Increasing social acceptance with awareness	36	19
Increasing social acceptance with social benefits	37	19.6
Making legal arrangements (suggestions etc.)	38	20.1
Establishing geothermal standards	26	13.8
Offering plant-based incentives (rewards, for drilling costs, etc.)	12	6.3
Promoting domestic equipment production/use	8	4.2

4.3.2.1. Current Opportunities

Interviewees pointed to the country's strong potential for electricity generation, ranking first in Europe and fourth globally in terms of installed capacity. One participant from an energy consultancy firm even suggested that the current capacity

of 1,600 MWe could reach 4,500 MWe. They argued that focusing solely on geothermal energy's relatively small share in total electricity generation can be misleading. Instead, they emphasized that geothermal energy is more efficient than other renewable sources, with a high capacity factor exceeding 90%, allowing it to operate as a baseload resource.

Many participants argued that the country should also focus on its potential for direct utilization, rather than solely on electricity generation. They pointed out that geothermal resources are already present in 63 cities across Türkiye, with a wide range of applications, from heating and cooling to thermal tourism and the drying of fruits and vegetables. One of the interviewees (#19) stated:

> Türkiye possesses substantial geothermal potential. Our primary focus has been on Western Anatolia due to its economic feasibility. Moving eastward, we must drill deeper into reservoir rocks to reach hot rocks, leading to higher drilling costs. While there is a gradual shift towards Central Anatolia, various regions in Türkiye hold significant potential for electricity production. However, the thicker crust in Eastern Anatolia presents a more challenging task requiring additional effort and financial resources. Despite these challenges, geothermal heating can be effectively utilized in a significant part of Türkiye.

They drew attention to the fact that geothermal resources could bring considerable advantages to the locals regarding district heating and reduce their heating costs, considering high imported energy prices. One of the interviewees (#20) insisted:

> Heating 80% of Türkiye with geothermal energy is feasible. Even with natural gas, geothermal energy would still result in significant savings, approximately 30%, in these regions. When evaluating the payback period for investments in regional heating, it is crucial to consider the reduced costs associated with using geothermal energy instead of natural gas, along with the impact on employment and the social benefits it would provide. For instance, transitioning to geothermal-based regional heating in areas where central heating systems are already in place could be much easier. Promoting regional heating with geothermal energy sources instead of individual heating would be both a more economical and environmentally friendly approach.

Besides offering a reasonable solution to the heating problem, geothermal energy would also contribute to the regional development of rural areas not yet served by natural gas.

Geothermal greenhouse projects could increase employment opportunities for locals, particularly women. In addition to these economic benefits, direct utilization practices can be highly effective in increasing social acceptance and improving local attitudes toward geothermal energy.

The respondents stated that the Turkish geothermal energy sector increased its human resources, know-how and experience along with technological advances. One of the interviewees (#8) suggested:

> There are thousands of oil wells in Türkiye that have the potential to produce not only oil and natural gas but also geothermal energy. The seismic structure and rock pressures of all oil fields are well-known. The existing knowledge about the underground conditions in oil wells is a significant advantage that can substantially reduce the initial investment costs for geothermal projects.

The participants appreciated the existence of financial support mechanisms to cover the costs of drilling, such as RSM and technical assistance offered to investors today. Thus, it is time for Türkiye to focus on emerging geothermal technologies, such as hot dry rock, which offer a power generation potential of up to 400,000 MWe for the country. Türkiye should also accelerate its effort to hybridize geothermal energy with other technologies. Given most geothermal plants in the country are binary ORC systems with air-cooled condensers, their efficiency and electricity generation decline during summer due to higher air temperatures (Gutiérrez-Negrín, 2024). Thus, hybridizing geothermal power with solar or wind energy to enhance power generation or supply the plant's self-consumption was frequently stated as a promising development.

The interviewees also emphasized the importance of geothermal energy in achieving the emission reduction targets envisaged under the Paris Climate Agreement, highlighting it as a domestic, non-intermittent and environmentally friendly energy source. They noted that Türkiye's high geothermal potential represents a strategic asset in the country's rapidly accelerating green transition. Although geothermal power plants in Türkiye, particularly those located in the Büyük Menderes and Gediz Basins, currently exhibit relatively high CO_2 emission levels compared to the global average, these emissions are expected to decline over time due to decreasing

reservoir CO_2 content and the implementation of CO_2 non-condensable gas reinjection practices (Babür, 2025).

4.3.2.2. Future Opportunities

Interviewees regarded low social acceptance and local resistance to geothermal projects as one of the most critical challenges and underlined that these issues could be overcome by increasing public awareness and providing benefits to local communities. One of the interviewees (#12) commented:

> A geothermal project can no longer be carried out despite the locals. In this context, pondering on social acceptance is critical. People should first be sufficiently knowledgeable about the resource. This can be achieved through the education system. This is one of the reasons why post-acknowledgment struggles become insufficient. A person naturally fears what he does not know. For this reason, the government, other relevant institutions, NGOs and local administrations should work together and answer the questions of the local people.

The other (#9) stated: "*By not only generating electricity but also heating the houses and building greenhouses, providing local employment, the more people you touch in this way, the more you will make these people embrace the geothermal*. "

The participants also noted that Türkiye should support its know-how on geothermal energy with new technologies and focus on the academia-industry collaboration while accelerating R&D activities and offering project-based incentives. Furthermore, establishing new geothermal-specific standards, rather than relying on those developed for oil or other conventional resources, was also regarded as a future opportunity by the interviewees.

Besides other suggestions, such as offering incentives to efficient and well-operated plants and promoting the production and use of domestic equipment, respondents also proposed several legal arrangements. These proposals centred on establishing a governmental institution dedicated to geothermal energy, prioritizing geothermal development in national strategic planning, revising the current incentive scheme and making direct utilization applications mandatory for new electricity generation projects.

4.4. Conclusion and Policy Implications

As a domestic, clean and non-intermittent energy resource, geothermal energy offers numerous advantages to resource-rich countries, among which Türkiye stands out with its considerable potential. However, its development still faces significant challenges that the country should address to unlock its full potential.

This study explores the opportunities and challenges of geothermal energy in Türkiye, drawing on the views of key stakeholders as a complement to the preceding TIS chapter. Although the TIS analysis of geothermal diffusion in Türkiye provided valuable insights, supported by document analysis and market data, the interviews captured stakeholder opinions and concerns while also highlighting key issues and areas of agreement and disagreement. To the best of our knowledge, this study represents the first comprehensive qualitative analysis of the Turkish geothermal sector, providing a holistic understanding of its institutional, technical, economic, social and environmental dimensions of geothermal development.

Interviews conducted with different stakeholders revealed varying priorities and concerns regarding the expansion of geothermal energy. Stakeholders affected by developments in the geothermal sector frequently expressed dissatisfaction with the current situation, whereas policymakers shaping geothermal development were more optimistic about the future. While plant operators or technology developers were primarily concerned with financial and economic challenges, investment enterprises facilitating this financial support were more focused on environmental and social issues. Overall, these findings highlight the diversity of stakeholder perspectives and underscore the need for more integrated policy approaches that balance the expectations and priorities of different stakeholders.

The findings from the interviews indicated that Türkiye possesses significant geothermal potential that can be further developed through the integration of new technologies and existing know-how. Nonetheless, geothermal energy development in the country continues to be constrained by political, regulatory and institutional; financial and economic; technical; and environmental and social barriers.

Among the institutional and regulatory barriers, a fragmented market structure, the underdevelopment of direct-use applications, inadequate monitoring and auditing, the lack of institutional coordination and lengthy approval processes remain prominent. Financial constraints are primarily linked to high upfront investment costs, the current YEKDEM scheme and the absence of targeted incentives for direct utilization. On the technical side, the need for further technological advancement, enhanced knowledge development and sustainable reservoir management persists, alongside existing technical deficiencies. Meanwhile, low social acceptance of geothermal energy stands out as the most significant environmental and social barrier.

Based on insights derived from the interviews, Türkiye should prioritize the sustainable development of geothermal energy, particularly after gaining significant momentum in recent decades. While TIS analysis underscores the role of YEKDEM in stimulating geothermal investments, interviewees largely attribute the recent slowdown in the growth of the geothermal power sector to the current design of the incentive scheme. Indeed, the slowdown observed in the geothermal power sector following the 2021 revisions to YEKDEM, which reduced returns for plant operators, underscores the critical importance of financial support for attracting geothermal investments. Despite its considerable potential, geothermal energy still requires greater incentives due to its high upfront capital costs compared to other renewable energy sources. Furthermore, uncertainty arising from frequent policy changes and prevailing economic conditions in the country is a key determinant of the trajectory of geothermal investments.

Direct utilization of geothermal energy is feasible in many parts of Türkiye and can offer significant advantages, such as reducing dependence on natural gas for heating, supporting regional development, creating local employment and enhancing social acceptance. In this regard, introducing new financial incentives for direct utilization or imposing legal obligations on plant operators to ensure the integrated use of geothermal energy could effectively promote the wider adoption of direct utilization practices.

The TIS analysis indicates that local expertise in the Turkish geothermal energy sector has not yet been sufficiently translated into domestic technological

development through R&D activities. Consistent with this finding, interviewees emphasized that leveraging Türkiye's accumulated human capital and technical expertise through stronger R&D support and stakeholder collaboration could reduce the sector's reliance on imported equipment. This can be further accelerated through increased support for R&D activities, enhanced knowledge exchange between investors and researchers and stronger collaboration among stakeholders.

To minimize bureaucratic processes and conflicts between investors and landowners or local communities, the centralized management of geothermal energy under a principal institution is of critical importance as frequently emphasized during the interviews. This could also enable investors to implement ongoing projects more efficiently and encourage further investment.

The TIS analysis reveals the fragmented structure of the geothermal power sector, while interviewees indicate that this pattern of market development has contributed to environmental problems and low social acceptance, particularly due to improper practices by small-scale and non-institutional operators. These findings highlight the need for more stringent and systematic monitoring mechanisms for geothermal projects to prevent environmental damage and ensure reservoir sustainability.

Improved economic and social benefits, combined with reduced environmental impacts, can foster more positive attitudes among local communities and significantly reduce resistance to new geothermal projects. Moreover, promoting community engagement through continuous dialogue and transparent information-sharing with local stakeholders prior to project implementation, as well as integrating geothermal energy into school curricula, can substantially enhance public awareness and social acceptance in Türkiye.

As emphasized by the interviewees, social acceptance of geothermal energy varies significantly across different regions of Türkiye. Notably, while local communities in some regions are satisfied with geothermal development, others strongly oppose it. These contrasting attitudes toward the same resource raise important questions. In this regard, several factors may serve as key determinants of social acceptance,

including the extent to which local communities benefit from the direct utilization of geothermal energy and the characteristics and practices of the companies operating in these regions. Therefore, further research addressing this issue is essential to deepen the understanding of the social acceptance of geothermal energy in Türkiye and to provide valuable insights for countries at the early stages of their geothermal development.

CHAPTER 5

CONSTRUCTION OF A SOCIAL ACCOUNTING MATRIX FOR THE TURKISH GEOTHERMAL ENERGY SECTOR AND MULTIPLIER ANALYSIS

The stakeholder interviews presented in the previous chapter highlight the significant economic and social benefits that geothermal energy can provide through its integrated use for electricity and heat generation in Türkiye. Building on these findings, this chapter develops a Social Accounting Matrix (SAM) for the Turkish geothermal energy sector and examines the economy-wide impacts of exogenous commodity demand shocks and increased investment in electricity generation, with particular emphasis on geothermal heat generation.

5.1. Fundamentals of Social Accounting Matrix

The origins of the Social Accounting Matrix, SAM, trace back to the Cambridge Growth Project initiated by Richard Stone and Alan Brown in the early 1960s. Following the construction of the first SAM for this work, Pyatt and Thorbecke (1976) formulated the concept of SAM and offered a formal framework for policy and planning purposes. Other early studies such as Pyatt and Round (1977), Pyatt and Round (1979), Defourny and Thorbecke (1984) and Thorbecke (1995) also significantly contributed to the rapid development of SAM literature.

SAM as a complete database shows all economic transactions and income transfers between the economic agents in a certain period of time. SAM, which incorporates both social and economic data, is broader in scope than Input-Output (I-O) tables and standard national accounts. Thorbecke (2000) underlines that SAM presents a detailed and disaggregated picture of socioeconomic dynamics for a given year. In

terms of geographical coverage, SAM can be developed at the national, regional, or sub-regional levels. Even though there are no strict data-compiling requirements for SAM; I-O tables, national accounts, supplementary data in public finance comprise the main data sources of SAM (Erdoğan, 2011). Indeed, the I-O tables displaying only sectoral linkages through flows of intermediate inputs can be extended to capture income and expenditure flows between other institutions, such as households, government and the Rest of the World (RoW) (Reinert & Roland-Holst, 1997). SAM offers a meso-level framework combining a macro perspective with a more detailed description of markets and institutions (Round, 2003).

SAM, as an extension of the I-O table examining inter-sectoral dependence and linkages, but with more emphasis on distributive aspects, shows how sectoral value added is distributed to the factors of production and how these incomes along with transfers are spent and lead to further sectoral production and value-added. Moreover, the leakages from this economic cycle such as foreign payments or savings are also included in SAM and savings are associated with capital finance to capture broader economic dynamics (Keuning & De Ruuter, 1988). When following this circular flow for households as illustrated in Figure 5.1, households acquire factor incomes such as wage and profit from factor markets, social transfers from the government and remittances from RoW and they spend this income for the purchase of goods and services at commodity markets, tax payments to government and private savings as investment.

Unlike the I-O tables focussing only on the relationship between production and final demand, SAM reveals how the production process affects and determines the demand (Cansino et al., 2014). Furthermore, SAM multipliers reveal all direct and indirect (along with consumption and production linkages) impacts of an external shock, I-O multipliers only capture them through production linkages (Breisinger et al., 2010).

Round (2003) summarizes three main features of the SAM: it explicitly shows all interconnections between the agents, it displays all economic activities in the system such as consumption, production, accumulation and distribution and lastly, it is

flexible in terms of disaggregation. Indeed, there is no standard way of disaggregation or organization of data in a SAM and country or region-specific features or the objectives of the study can determine the structure of a SAM (Thorbecke, 1998).

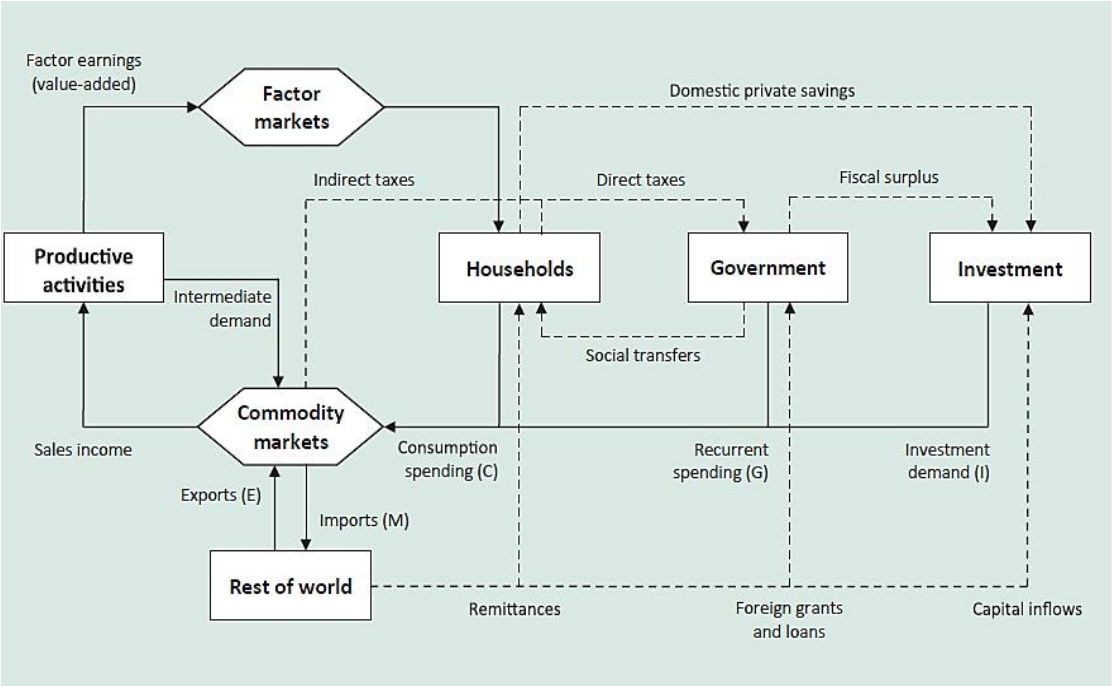

Figure 5.1. Circular flow diagram of the economy

Source: Breisinger (et al., 2010)

Besides being a comprehensive, consistent and complete database, SAM also provides a conceptual framework for policy analysis and exploration of the impacts of exogenous shocks or changes (Thorbecke, 1998). In an ex-ante setting, the SAM enables the analysis of the partial equilibrium impacts of real shocks through a multiplier model that internalizes the circular flow of income (Round, 2003). In addition to providing a dataset for economic modelling, SAM also offers a benchmark equilibrium for Computable General Equilibrium (CGE) models and it is used to calibrate the parameters of these models (Karadag & Westaway, 1999). In this way, SAM, from simple linear multiplier models to more complicated CGE models, serves as a tool to analyse a wide range of issues, including employment, taxation, productivity, trade, poverty and inequality, economic development, technological change and environmental aspects (Mainar-Causapé et al., 2018).

Despite its clear advantages, SAM also has several limitations along with its some strong assumptions, as discussed by Erik Thorbecke (2000) and Hartono et al. (2020a). Firstly, SAM analysis assumes that the prices are fixed and exogenous, i.e., the change in the demand has no impact on the prices. Secondly, it assumes unlimited factors of production such as capital, labor and land. Based on these two restrictions, SAM can be regarded as a demand-driven model along with an excess capacity assumption, in which any increase in demand can be supported by an immediate increase in output owing to the availability of abundant resources in the economy (Akkemik, 2012). Lastly, using national SAM instead of interregional one can disregard the regional differences. Hartono and Resosudarmo (2008) also add other drawbacks of the SAM regarding its static structure and technology assumption. Since the SAM represents a static equilibrium, it may not fully capture long-run structural changes, as the structure of the economy and the underlying parameters evolve over time. Furthermore, SAM assumes fixed Leontief technology, in which technologies are constant from the base year of the model until a particular period (usually 5 years), which may not be realistic. Lastly, the results of SAM analysis should be interpreted in terms of magnitudes, directions and distributive patterns rather than numeric values (Fathurrahman et al., 2017). Nevertheless, despite these limitations, SAM remains a valuable analytical framework for examining sectoral linkages, distributional effects and the economy-wide impacts of policy interventions or exogenous shocks.

5.2. Structure of SAM

Each row and column of the SAM as a square matrix is called an “account” and while rows correspond to incomes (receipts) for the related sector or institution, the columns indicate its expenditures (payments). Based on the principle of double-entry accounting, the sum of rows and columns for an account should be equal, i.e., the total payment should be equal to the total receipt for each account (Breisinger et al., 2010). Furthermore, since SAM is designed to represent an ex-post equilibrium state of an economy, where all markets are cleared and the receipts and payments of funds are balanced for every agent, this equality condition constitutes a crucial prerequisite for SAM-based analyses (Hosoe et al., 2010).

Table 5.1. Basic structure of SAM

	Activities	**Commodities**	**Labor**	**Capital**	**Household**	**Government**	**Savings**	**Rest of the World (RoW)**	**Total**
Activities		Supply for the domestic market						Exports	**Gross production / Total sales**
Commodities	Intermediate input demand				Private consumption	Public consumption	Investment		**Aggregate demand**
Labor	Wages								**Labor income**
Capital	Profits								**Capital income**
Household			Wage income	Profit income		Social transfers		Foreign remittances	**Private income**
Government		Indirect taxes on sales & import tariffs			Direct taxes and non-tax payments			Foreign savings	**Public income**
Savings					Private savings	Public savings			**Total savings**
Rest of the World (RoW)		Imports				Interest payments on foreign borrowing			**Payments to RoW**
Total	**Gross output / Production costs**	**Aggregate supply**	**Total wages**	**Total profits**	**Total private expenditure**	**Total public expenditure**	**Total investment**	**Income from RoW**	

Source: Author's compilation based on Karadag (1997), Telli (2004), Erten (2009), Breisinger (et al., 2010), Kılınç (2022) and Ipek (2023)

The SAM constructed for this study consists of seven main accounts as given in Table 5.1, i.e., activities, commodities, factors of production (labor and capital), household, government, investment (savings) and the Rest of the World (RoW).

Activities are the entities producing goods and services, i.e., commodities. During the production process, they make expenditures on the purchase of intermediate goods and distribute value added to factors of production. The goods produced by these activities are supplied to the domestic market and/or exported. On the other hand, commodities are supplied by both domestic production and foreign markets (imports) and are subject to indirect taxes paid to the government. These commodities meet aggregate domestic demand, which consists of intermediate input demand, consumption (private and public) and investment (private and public)

Households receive income in the form of wages and profits as owners of factors of production and get transfer payments from the government and the RoW. Then, they purchase commodities, pay taxes directly to the government and make private savings.

The direct and indirect tax revenues and transfers from abroad constitute the government income. The government utilizes it to purchase commodities, make transfers to households and interest payments on foreign borrowing and make public savings. Indeed, private and public savings serve as investment expenditures.

Lastly, RoW receives income from imports and government interest payments and uses it for making payments on exports and foreign remittances to households and transferring foreign savings to the government.

5.3. Mathematical Representation of SAM Multiplier Analysis

For the shock analysis, some accounts in the SAM are assigned as exogenous and the remaining as endogenous. In practice, however, there are no strict rules governing this classification. Factors, institutions (including firms and households) and production activities are assumed endogenous in general, while government, capital

accumulation and the RoW are exogenous (Defourny & Thorbecke, 1984). Indeed, exogenous accounts typically consist of those relevant to policy formulation and directly or indirectly manipulated by decision makers such as the government account (Bellù, 2012) and those determined outside the model such as capital accounts, indirect taxes and subsidies and the RoW (Fathurrahman, 2014). In this study, the accounts of activities, commodities, factors of production and households are taken as endogenous; government, investment and the RoW as exogenous. The shock is given to the exogenous accounts and its impacts on income, production and consumption levels within the endogenous ones are examined through the SAM multiplier analysis (Akkemik, 2012).

Table 5.2. Simplified SAM framework

			EXPENDITURES					
			Endogenous accounts				***Exogenous accounts* (5)**	**TOTAL**
			Activities (1)	Commodities (2)	Factors (3)	Household (4)		
RECEIPTS	***Endogenous accounts***	Activities (1)	0	T_{12}	0	0	X_1	Y_1
		Commodities (2)	T_{21}	0	0	T_{24}	X_2	Y_2
		Factors (3)	T_{31}	0	0	0	0	Y_3
		Household (4)	0	0	T_{43}	0	X_4	Y_4
	***Exogenous accounts* (5)**		0	T_{52}	0	T_{54}	X_5	Y_5
	TOTAL		Y'_1	Y'_2	Y'_3	Y'_4	Y'_5	

The simplified SAM framework for this study is presented as a 5∗5 matrix in Table 5.2. In the submatrix $T_{ij,}$ the subscript "i" represents the economic agent acquiring the income, while "j" denotes that making the expenditure. To illustrate, T_{12} corresponds to the income of the "activities" account generated by providing outputs to the domestic markets, i.e., to the "commodities" account, while T_{21} refers to the income of the "commodities" account acquired from the sale of intermediate good to the "activities" account. Moreover, the total expenditure is equal to the total receipt for each account, i.e., $Y_i = Y'_i$.

Income distributions of endogenous accounts can be mathematically expressed as $Y_i = \sum_j T_{ij} + X_i$ for i, j = 1, 2…5. On the other hand, the share of expenditures of each

account, i.e. average expenditure propensities, can be calculated by dividing the element in any cell in the endogenous accounts by the total of the corresponding column account such as $A_{ij} = T_{ij}Y_j^{-1}$ or $T_{ij} = A_{ij}Y_j$. Here, A_{ij} represents the ratio of expenditure in row-i and column-j; T_{ij} is the entry of matrix T in row-i and column-j and Y_j is a diagonal matrix representing the total expenditure of column-j.

The SAM framework can be formulated in the matrix form as follows:

$$\begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ Y_4 \end{bmatrix} = \begin{bmatrix} 0 & A_{12} & 0 & 0 \\ A_{21} & 0 & 0 & A_{24} \\ A_{31} & 0 & 0 & 0 \\ 0 & 0 & A_{43} & 0 \end{bmatrix} \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ Y_4 \end{bmatrix} + \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix}$$

Or can be re-written as (Defourny & Thorbecke, 1984):

$$\mathbf{Y = AY + X \rightarrow Y - AY = X \leftrightarrow (1-A)Y = X \leftrightarrow (I-A)^{-1}X \leftrightarrow Y = M_a X} \quad (1)$$

Alternatively, this equation can be expressed in terms of changes, i.e., $\Delta\mathbf{Y} = \mathbf{M_a}\Delta\mathbf{X}$ (2)

Here $(I-A)^{-1} = M_a$ is called the multiplier matrix, accounted multiplier matrix, or Leontief inverse matrix. It demonstrates that one unit change in the exogenous account (X) or final demand will impact the endogenous account (Y) by M_a. As the most basic form of SAM analysis, the unconstrained multiplier model, as specified in Equations (1) and (2), is primarily based on the assumption that supply can fully respond to changes in demand, or that supply capacity is unlimited given existing resources (Breisinger et al., 2010).

In this multiplier analysis, the economy-wide impact calculated via the Leontief inverse matrix can be expressed in terms of direct, indirect and induced impacts, as clarified in Alkan (2018). While "*direct impact*" refers to production changes in the sector directly affected by the exogenous shock, "*indirect impact*" captures production changes in input-supplying sectors driven by shifts in the input requirements of the sector directly affected from the shock. On the other hand, "*induced impact*" reflects additional household consumption triggered by employment changes arising from direct and indirect effects. Indeed, through a

feedback, factor incomes generated by activity's production circulate through institutional expenditures and eventually return to stimulate the activity's own production (Pal et al., 2012).

To calculate the direct, indirect and induced impacts in this study, two modelling approaches is used, as clarified in Cardenete and Sancho (2004) and Juana and Mabugu (2005). The direct and indirect impacts are derived from the standard input-output model. Meanwhile, the induced impacts are obtained as the difference between the enlarged SAM model and the initial input-output model, when factors of production (labor and capital) and households are also treated as endogenous in addition to activities and commodity accounts.

In this study, the SAM multiplier analysis serves as a foundation for the more comprehensive CGE model, which is introduced in the next chapter. Indeed, this analysis is used to capture short-run demand-driven effects under fixed prices and excess capacity assumptions. On the other hand, the CGE model incorporates price adjustments and factor market constraints, allowing for the analysis of economy-wide general equilibrium effects.

5.4. Literature on Energy-based SAM Multiplier Analysis

Early studies of SAM mostly concentrate on combining I-O table and income distribution data in a unified framework based on Richard Stone's research in the 1960s and 1970s (Robinson, 1989). Over time, the SAM literature has rapidly expanded, with studies using SAM either as a database for multiplier analysis or for CGE models. Given its critical role in the overall economy, the energy sector has been increasingly incorporated into the SAM-based analyses as a key component.

Energy-based SAM multiplier analysis studies can be mainly classified into those examining the impacts of energy-related shocks, such as price shocks, demand changes and increases in energy-sector investment, as in Parra and Wodon (2008), Akkemik (2011), Hartono et al. (2020a), Kanitkar (2020), Effendi and Resosudarmo (2022) and Azzahrah et al. (2023); those evaluating the economy-wide impacts of

energy policies, including energy price reforms, subsidy policies, carbon taxation and renewable energy incentives, as in Şenerdem (2013), Fathurrahman et al. (2017), Kılınç (2022), Mardones (2023) and Rahma et al. (2025); and those integrating the environmental dimension into SAM analysis, such as pollution emissions, depletable resources, energy and natural resource use, commonly referred to as Environmentally Extended SAM applications, as in Gallardo and Mardones (2013), Pal and Pohit (2014), Banerjee et al. (2019), Verma (2021) and El Meligi et al. (2025).

Despite the growing body of energy-based SAM research, the studies focusing exclusively on a specific renewable energy source have been remained relatively limited. Among these studies, Allan et al. (2011) apply SAM multiplier analysis to reveal the potential local economic and employment impacts of a large onshore wind energy project proposed for the Shetland Islands in Scotland. On the other hand, Gómez et al. (2013) evaluate the socio-economic impacts of deploying concentrated solar power technologies in Spain in terms of sectoral economic linkages, income distribution and employment based on an extended SAM approach. Similarly, Farag and Komendantova (2014) examine the potential impact of investments in the renewable energy project DESERTEC on Egypt's socioeconomic development. In another study, Joshi and Sharma (2018) center on the impacts of grid-connected solar PV utilization in India on economic growth and household income generation.

Overall, technology-specific energy SAM multiplier analyses predominantly focus on project-based impacts. On the other hand, studies focusing on geothermal-based scenarios using SAM multiplier analysis have been relatively few and are largely concentrated in Indonesia, a country with substantial geothermal potential.

Among the SAM multiplier analysis studies offering significant inferences for geothermal energy, Hartono et al. (2020a) simulate the impacts of a 1 GW power plant investment in coal-fired and renewable energy-based power plants such as geothermal, hydro, wind and solar on the value-added (GDP), employment and CO_2 emissions for Indonesia. The results reveal that geothermal and wind power plants offer the highest net GDP (0.66% and 0.67%) and employment (0.57% and 0.70%) to the economy despite their high investment requirement and emissions during

power plant construction. Moreover, investment in the geothermal power sector leads to an increase in GDP and employment mainly in the sectors of mining and quarrying, electricity, gas and water supply, construction, transportation and communication, finance, real estate and company services. Similarly, Azzahrah et al. (2023) focus on the simulation of the impacts of a 1 GW investment in renewable power plants, including hydro, biofuels and geothermal in Indonesia and conclude that the construction of geothermal power plants generates the largest increases in GDP (0.76%), employment (0.65%), household income (0.70%) and CO_2 emissions (0.91%).

In contrast to other renewables that are primarily utilized for electricity generation, geothermal energy can provide both electricity and heat, enabling integrated use of the resource (Iordache & Ionescu, 2023). For investors, instead of using geothermal energy separately for different applications, which can be costly due to high initial capital costs, utilizing geothermal fluids multiple times through cascading systems can maximize overall benefits and improve project economic viability (Lund, 2010). For local communities, this can generate significant social benefits, including lowered heating costs, reduced emissions, enhanced energy independence, increased employment opportunities and stimulated economic growth (Kaczmarczyk & Sowiżdżał, 2025).

As reflected in the views of the Turkish stakeholders presented in Chapter 4, geothermal energy can provide significant economic and social benefits through its integrated use for electricity and heat generation in Türkiye as well. However, providing clear and quantifiable evidence of these benefits is essential, particularly to inform policy decision-making. Building on this perspective, primary objective of this study is to quantitatively assess the economic impacts of integrated use of geothermal energy relative to alternative energy sources, as well as the expansion of the electricity sector compared with other sectors.

Considering the limited number of SAM multiplier analysis studies on geothermal-specific scenarios across different country contexts, this paper aims to make a valuable contribution to the literature by providing insights from the Turkish case, as

another geothermal-rich country. Furthermore, the methodological approach adopted for the detailed disaggregation of the electricity sector, particularly the separation of the geothermal energy sector into geothermal electricity and geothermal heat generation, introduces a new dimension to geothermal energy-based SAM multiplier analysis. To the best of our knowledge, this research represents the first attempt to explicitly incorporate geothermal heat generation into a SAM multiplier framework. Finally, the SAM constructed for this study can serve as one of the most recent and detailed dataset for future CGE model applications on Türkiye's energy sector.

5.5. Determination of the Sectoral Structure of GEOSAM

After determining the general structure of SAM used in this study, hereafter referred to as GEOSAM, as presented in Table 5.1, the next step is to identify the sectors to be included in the "Activities" account. Given that the main focus of this study is geothermal energy development, sectors that either supply inputs to the geothermal industry or utilize its outputs are included as GEOSAM sectors. For this purpose, previous studies conducting sectoral analyses on geothermal energy, such as Jiang et al. (2019), Hartono et al. (2020a) and Azzahrah et al. (2023), are used as references. Additionally, expert consultations in the Turkish geothermal energy sector were conducted to validate and finalize the sector list. The most recent I-O table published for 2023 by Turkish Statistical Institute (TurkStat) in 2025 based on the Statistical Classification of Economic Activities in the European Community NACE Rev.2, includes 64 sectors. Building on the objectives of this study and insights from the literature and expert consultations, these 64 sectors are aggregated into fifteen sectors, as given in Table 5.3.

Out of these 15 sectors, those that provide input for the geothermal sector are classified as mining and quarrying, petroleum, chemicals, machinery and equipment, electronics, construction and material, transportation and communication, finance, insurance and real estate. Indeed, the drilling, machinery and equipment and construction sectors account for more than 70% of industry weights for geothermal (Pollin et al., 2015). Since drilling costs highly depend on the business cycles of the oil industry, petroleum is also a critical input for drilling activities, especially for the

geothermal sector. Furthermore, transportation services are needed to deliver equipment and materials and to carry field personnel during the exploration and operation of geothermal facilities. On the other hand, geothermal energy offers input for electricity and heat generation, agriculture and fishing, food processing, textile and clothing, hotels and restaurants and the real estate sector. In this study, geothermal energy is assumed to contribute to hotels and restaurants through thermal tourism, while the presence of geothermal resources is assumed to increase the value of the real estate in the areas where they exist. Moreover, the food processing, textile and clothing sectors that rely heavily on heat for various processes can benefit from geothermal energy. They can utilize large amounts of low-temperature energy from geothermal for washing and cleaning purposes (Popovska, 2001). Lastly, geothermal energy is used in the production of various chemical products and in the recovery of carbon dioxide from geothermal fluids for dry ice production (Akkuş & Alan, 2016).

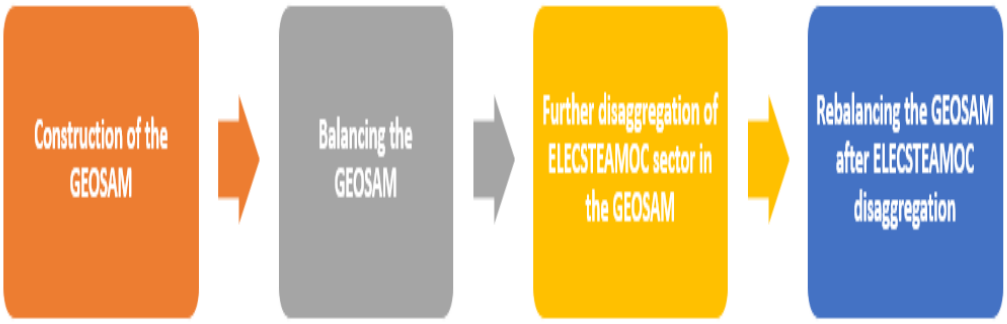

Figure 5.2. Steps to construct the final GEOSAM

After constructing the initial GEOSAM with the sectoral disaggregation presented in Table 5.3, the matrix is first balanced to ensure consistency by equalizing the row and column sums, as described in the following sections. Once this balanced benchmark matrix has been established, a further disaggregation is applied to the *Electricity, gas, steam and air conditioning* sector in order to distinguish different electricity generation technologies and geothermal heat production. Since this additional disaggregation may introduce imbalances within the accounting framework, the GEOSAM is subsequently rebalanced to restore the equality between row and column totals while preserving the consistency of the dataset. The overall procedure followed in constructing the final GEOSAM is summarized in Figure 5.2.

Table 5.3. Sectoral aggregation of the GEOSAM

Abbreviation	GEOSAM aggregated sector	Codes	Economic activity definitions from TurkStat I-O 2023 Table (NACE Rev.2)
AGRF	AGRICULTURE, FORESTRY&FISHING	A-01 A-02 A-03	Products of agriculture, hunting and related services Products of forestry, logging and related services Fish and other fishing products; aquaculture products; support services to fishing
MIN	MINING&QUARRYING	B	Mining and quarrying
FODPR	FOOD PROCESSING	C10-C12	Food, beverages and tobacco products
TEXCLOT	TEXTILE&CLOTHING	C13-C15	Textiles, wearing apparel, leather and related products
RPETR	REFINED PETROLEUM	C-19	Coke and refined petroleum products
CHE	CHEMICALS	C-20 C-21 C-22	Chemicals and chemical products Basic pharmaceutical products and pharmaceutical preparations Rubber and plastic products
MACHEQ	MACHINERY&EQUIPMENT	C-25 C-28	Fabricated metal products, except machinery and equipment Machinery and equipment n.e.c.
ELECTRO	ELECTRONICS	C-26 C-27	Computer, electronic and optical products Electrical equipment
OTHMAN	OTHER MANUFACTURING	C-16 C-17 C-18 C29 C30 C31-C32 C-33	Wood and of products of wood and cork, except furniture; articles of straw and plaiting materials Paper and paper products Printing and recording services Motor vehicles, trailers and semi-trailers Other transport equipment Furniture and other manufactured goods Repair and installation services of machinery and equipment
ELECSTEAMOC	ELECTRICITY, GAS, STEAM AND AIR CONDITIONING	D-35	Electricity, gas, steam and air conditioning
CONSMAT[10]	CONSTRUCTION & MATERIAL	C-23 C-24 F	Other non-metallic mineral products Basic metals Constructions and construction works
HOTRES	HOTELS &RESTAURANTS	I	Accommodation and food service services
TRANSCOM	TRANSPORTATION& COMMUNICATION	H-49 H-50 H-51 H-52 H-53 J61	Land transport services and transport services via pipelines Water transport services Air transport services Warehousing and support services for transportation Postal and courier services Telecommunications services
FIRE	FINANCE, INSURANCE & REAL ESTATE	K-64 K-65 K-66 L68B L68A	Financial services, except insurance and pension funding Insurance, reinsurance and pension funding services, except compulsory social security Services auxiliary to financial services and insurance services Real estate services excluding imputed rents Imputed rents of owner-occupied dwellings
OTH	OTHERS	The rest of the 64 sectors	The remaining ones from 64 sectors

[10] These three sectors were aggregated to represent the construction-related supply chain, as they include non-metallic mineral products (e.g., cement and concrete), basic metals (e.g., steel and iron products) and construction activities, which together provide the key materials and construction services required for the development of geothermal power plants and associated infrastructure.

5.6. Construction of the GEOSAM

The SAM for this study is constructed using various administrative data sources, with the 2023 I-O table serving as the primary dataset. By relying on the most recent I-O table rather than updating an older version through numerous assumptions, the SAM developed within the scope of this study offers a more reliable and internally consistent database for analyses. In addition, earlier studies on the construction of SAMs for Türkiye, such as Telli (2004), Erten (2009), Kılınç (2022) and İpek (2023), are reviewed in detail to inform the methodological framework of this research.

In Table 5.1, the "Activities-Commodities" entry of SAM corresponds to the supply for the domestic market. This value is calculated as 45,053,793,396 kTRY by subtracting exports (7,299,428,314 kTRY) from total output (52,353,221,710 kTRY) in the I-O Table. For sectoral calculations, as stressed in Erten (2009), passing from the I-O Table to SAM, basic prices are converted into producer's prices by using taxes less subsidies for the components of final demand such as private consumption, public consumption, investment, change in inventories and exports of goods and services. This point is taken into account in the following related calculations.

The "Commodities-Activities" entry in the SAM represents intermediate input demand, encompassing goods and services utilized in producing other goods and services and corresponds to the 27,707,496,957 kTRY. "Commodities-Household" and "Commodities-Government" entries are equivalent to private and public consumption expenditures as 16,039,101,837 kTRY and 3,585,843,124 kTRY, respectively, reflecting how households and the government allocate their income to purchase commodities. Finally, the "Commodities-Saving" entry in the SAM denotes investment, expressed as gross capital formation and equal to 9,370,472,231 kTRY. All these data are derived from the I-O Table.

The "Labor-Activities" and "Capital-Activities" entries of the SAM show the factor payments for labor and capital as wages and profits, which also correspond to the income of the households in the SAM. Particularly, the factor payments for capital is calculated as the sum of gross operating surplus/ mixed income and other net taxes

on production. These two values in the I-O Table correspond to 7,755,515,400 kTRY and 16,338,311,995 kTRY, respectively.

The “Household-Government” and “Household-RoW” entries of the SAM illustrate the household social transfers from government and workers’ foreign remittances, respectively. The social transfers data as 619,497,015 kTRY is calculated based on the “2023 Annual Report” from Social Security Institution and the “2023 Interest Payments on Domestic Borrowing” data from the Ministry of Treasury and Finance. On the other hand, the workers’ foreign remittances are compiled from the “Balance of Payment Statistics” by the Central Bank of Türkiye as 4,635,457 kTRY.

The “Government-Commodities” entry of the SAM shows one of the revenue items of the government, coming from net taxes on products included as 2,997,641,670 kTRY in the I-O Table. On the other hand, the “Government-Household” entry of the SAM is the sum of direct tax and non-tax payments of households to the government. While “Non-Tax Income” data is obtained as 351,639,661 kTRY from the “General Government Revenues and Expenditures 2023” table published by the Presidency of Strategy and Budget, “Income Tax” data as 694,044,298 kTRY is collected from the “General Government Budget Revenues 2023” table by the Ministry of Treasury and Finance.

The “RoW-Commodities” entry of SAM, corresponding to imports, is given as 9,203,376,442 kTRY in the I-O Table. On the other hand, the “RoW-Government” entry of the SAM shows the transfers to the ROW from the government and is acquired from the “2023 Interest Payments on Foreign Borrowing” data in the “General Government Debt Service Statistics 2023” table by the Ministry of Treasury and Finance as 130,447,663 kTRY.

In the SAM, “Private Savings” for the households as 7,633,174,070 kTRY, “Public Savings” for the government as 1,737,298,161 kTRY and “Foreign Savings” for the RoW as 2,029,760,334 kTRY are computed based on the difference between the sum of income and expenditure values for the related economic agent.

After all calculations and derivations, the resulting GEOSAM obtained is presented in Appendix A.2.

5.7. Insights from the GEOSAM

Prior to further disaggregation, an examination of the GEOSAM 2023 data provides valuable insights into the structural characteristics of production and key macroeconomic variables within the economy. Total value-added, also referred as to GDP at factor costs, is the earnings received by the factors of production, such as the wages and salaries paid to labor and the profits paid to capital. As Table 5.4 shows, the Turkish economy is predominantly service-oriented, with OTH (38%), TRANSCOM (10%) and FIRE (10%) together accounting for nearly 60% of total GDP. In contrast, AGRF (7%) and manufacturing-related sectors such as food processing, textiles and chemicals together account for less than 10%, indicating limited industrial capacity. The CONSMAT (8%) remains a key non-service contributor of GDP. Furthermore, the sectors with the highest capital income shares are AGRF, ELECSTEAMOC, TRANSCOM and FIRE, while OTH, TEXCLOT, MACHEQ and HOTRES exhibit relatively higher labor income shares.

Table 5.4. Sectoral GDP at factor cost and GDP, labor and capital earning shares in 2023

Sectors	GDP at factor cost (kTRY)	GDP share (%)	Labor share (%) in its GDP at factor cost	Capital share (%) in its GDP at factor cost
AGRF	1,702,245,930	7.07	4.28	95.72
MIN	290,283,834	1.20	27.40	72.60
FODPR	798,079,070	3.31	25.99	74.01
TEXCLOT	734,127,181	3.05	43.72	56.28
RPETR	135,103,025	0.56	30.64	69.36
CHE	636,933,242	2.64	30.11	69.89
MACHEQ	787,184,773	3.27	37.29	62.71
ELECTRO	352,276,828	1.46	34.83	65.17
OTHMAN	1,177,482,967	4.89	31.83	68.17
ELECSTEAMOC	492,438,834	2.04	13.34	86.66
CONSMAT	1,994,083,157	8.28	32.48	67.52
HOTRES	934,764,011	3.88	37.08	62.92
TRANSCOM	2,411,304,763	10.01	16.99	83.01
FIRE	2,416,671,920	10.03	13.01	86.99
OTH	9,230,847,858	38.31	46.22	53.78

Table 5.5. Activity-commodity shares (%) in 2023

		ACTIVITIES															
		AGRF	MIN	FODPR	TEXCLOT	RPETR	CHE	MACHEQ	ELECTRO	OTHMAN	ELECSTEAMOC	CONSMAT	HOTRES	TRANSCOM	FIRE	OTH	TOTAL
COMMODITIES	AGRF	17.2	0.4	32.0	3.1	0.0	0.7	0.1	0.0	1.3	0.1	0.5	2.0	0.6	0.0	0.3	3.1
	MIN	0.2	11.9	0.2	0.2	68.1	1.0	0.5	0.3	0.4	18.6	3.8	0.1	1.0	0.0	0.2	2.9
	FODPR	2.4	0.3	16.2	0.6	0.1	0.5	0.3	0.1	0.3	0.1	0.7	14.1	0.4	0.1	0.6	1.8
	TEXCLOT	0.0	0.2	0.1	32.7	0.0	0.6	0.4	0.1	1.1	0.1	0.3	0.4	0.2	0.1	0.4	1.6
	RPETR	1.4	2.3	0.2	0.2	2.8	2.4	0.4	0.2	0.3	0.5	1.9	0.3	8.4	0.1	1.7	1.8
	CHE	5.4	2.6	2.7	7.5	0.7	40.5	3.7	6.4	6.4	0.3	2.9	0.9	0.9	0.6	1.0	3.9
	MACHEQ	0.0	2.6	0.5	0.7	0.2	1.7	13.8	3.9	6.0	0.5	4.4	0.5	0.6	0.3	4.4	3.2
	ELECTRO	0.0	0.7	0.2	0.4	0.1	0.5	2.9	20.2	3.3	1.1	1.9	0.6	0.8	0.3	4.3	2.5
	OTHMAN	0.4	1.3	1.1	1.8	0.3	2.2	3.4	3.4	17.1	0.4	2.2	1.0	2.2	0.6	2.3	2.9
	ELECSTEAMOC	0.8	5.2	1.6	3.8	1.9	2.1	1.8	1.1	1.9	52.8	3.4	2.4	1.0	6.6	1.5	5.0
	CONSMAT	0.3	4.0	0.5	0.5	0.2	2.2	24.6	18.9	11.8	0.7	31.4	0.8	0.6	1.4	1.7	7.5
	HOTRES	0.0	0.2	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.0	0.2	2.4	0.2	0.2	1.0	0.4
	TRANSCOM	1.1	5.4	3.3	2.2	2.4	3.1	3.1	2.8	4.1	1.3	3.8	2.2	18.1	1.0	4.4	4.6
	FIRE	0.3	3.2	1.4	1.8	0.6	1.5	1.7	1.6	1.8	1.9	1.7	3.0	3.3	12.4	4.3	3.2
	OTH	4.5	8.8	12.2	9.7	3.5	8.7	8.1	10.0	11.5	4.1	13.2	11.9	10.9	7.3	6.9	8.9
FACTORS OF PRODUCTION	LABOR	2.8	14.0	7.2	15.2	5.9	9.8	13.1	10.7	10.4	2.3	9.0	21.2	8.6	9.0	30.2	15.0
	CAPITAL	63.1	37.0	20.6	19.5	13.3	22.6	22.1	20.1	22.4	15.3	18.7	36.0	42.1	60.1	35.1	31.5

Table 5.5 presents the distribution of factor and commodity payments in gross output for 2023, reflecting the input requirements per unit of output across sectors. The OTH, CONSMAT, TRANSCOM and ELECSTEAMOC sectors are the main suppliers meeting the input demands of other sectors. Notably, the input share of AGRF for FODPR (32%), MIN for RPETR (68%), FODPR for HOTRES (14%), CONSMAT for MACHEQ (25%) and ELECTRO (19%), as well as OTH for several sectors such as CONSMAT (13%), FODPR (12%) and HOTRES (12%) and OTHMAN (12%) and TRANSCOM (11%), are particularly significant.

Table 5.6. Demand for commodities in 2023

Commodities	Intermediate demand (kTRY)	Private consumption (kTRY)	Public consumption (kTRY)	Capital accumulation (kTRY)	Total (kTRY)
AGRF	1,631,565,735	922,414,817	0	145,254,169	2,699,234,721
MIN	1,483,101,472	76,504,415	7,558,518	38,077,407	1,605,241,813
FODPR	957,126,093	2,269,426,723	0	-183,803,811	3,042,749,006
TEXCLOT	852,128,295	1,026,843,681	0	-44,431,157	1,834,540,820
RPETR	942,045,677	322,961,711	0	76,733,461	1,341,740,850
CHE	2,013,924,679	407,481,330	129,390,263	110,681,216	2,661,477,489
MACHEQ	1,642,446,469	81,642,141	0	1,660,599,634	3,384,688,245
ELECTRO	1,271,627,298	503,013,278	0	494,059,419	2,268,699,995
OTHMAN	1,495,583,445	1,435,630,802	6,082,404	1,586,219,759	4,523,516,411
ELECSTEAMOC	2,593,869,846	331,357,688	0	0	2,925,227,534
CONSMAT	3,908,440,301	111,150,947	67,339	4,215,252,999	8,234,911,586
HOTRES	228,595,648	1,443,728,413	0	0	1,672,324,062
TRANSCOM	2,384,911,247	1,478,319,278	52,165,639	114,990,516	4,030,386,681
FIRE	1,670,018,294	1,938,330,979	10,418,811	0	3,618,768,084
OTH	4,632,112,457	3,690,295,631	3,380,160,150	1,156,838,616	12,859,406,854
TOTAL	**27,707,496,957**	**16,039,101,837**	**3,585,843,124**	**9,370,472,231**	**56,702,914,149**

Tables 5.6 and 5.7 present the composition of commodity demand in 2023, highlighting the contributions of each commodity to intermediate demand, private and public consumption and capital accumulation. The figures indicate that OTH (23%) dominates total demand, reflecting its broad use across the economy. Intermediate demand is mainly concentrated in OTH (17%), CONSMAT (14%) and

ELECSTEAMOC & TRANSCOM (9%), emphasizing their importance as production inputs. In private consumption, OTH (23%), FODPR (14%) and FIRE (12%) stand out, showing their substantial contribution to household demand. Public consumption is overwhelmingly directed toward OTH (94%), mostly encompassing public services and administration.

Regarding capital accumulation, CONSMAT (45%), MACHEQ (18%) and OTHMAN (17%) are the major sectors, indicating that investment is largely directed toward construction, machinery and manufacturing.

Table 5.7. Demand for commodities shares in 2023

Commodities	Intermediate demand (%)	Private consumption (%)	Public consumption (%)	Capital accumulation (%)	Total (%)
AGRF	5.89	5.75	0.00	1.55	4.76
MIN	5.35	0.48	0.21	0.41	2.83
FODPR	3.45	14.15	0.00	-1.96	5.37
TEXCLOT	3.08	6.40	0.00	-0.47	3.24
RPETR	3.40	2.01	0.00	0.82	2.37
CHE	7.27	2.54	3.61	1.18	4.69
MACHEQ	5.93	0.51	0.00	17.72	5.97
ELECTRO	4.59	3.14	0.00	5.27	4.00
OTHMAN	5.40	8.95	0.17	16.93	7.98
ELECSTEAMOC	9.36	2.07	0.00	0.00	5.16
CONSMAT	14.11	0.69	0.00	44.98	14.52
HOTRES	0.83	9.00	0.00	0.00	2.95
TRANSCOM	8.61	9.22	1.45	1.23	7.11
FIRE	6.03	12.09	0.29	0.00	6.38
OTH	16.72	23.01	94.26	12.35	22.68

According to the household income and expenditure data presented in Table 5.8 and Table 5.9, the majority of household income (68%) is generated from capital payments. Government transfers and foreign remittances represent only a minor share of total income (3%). On the expenditure side, households allocate most of their spending to commodities from the OTH (15%), FODPR (9%) and FIRE (8%) sectors. Additionally, they save approximately 31% of their earnings, while about 4% is paid to the government as direct taxes.

Table 5.8. Sources of household income and their shares in 2023

Sources of income	Labor	Capital	Government	ROW
Household income (kTRY)	7,755,515,400	16,338,311,995	619,497,015	4,635,457
Household income (%)	32.19	67.81	2.57	0.02

Table 5.9. Distribution of household expenditure and their shares in 2023

Household		Expenditure (kTRY)	Expenditure (%)
COMMODITIES	AGRF	922,414,817	3.73
	MIN	76,504,415	0.31
	FODPR	2,269,426,723	9.18
	TEXCLOT	1,026,843,681	4.15
	RPETR	322,961,711	1.31
	CHE	407,481,330	1.65
	MACHEQ	81,642,141	0.33
	ELECTRO	503,013,278	2.04
	OTHMAN	1,435,630,802	5.81
	ELECSTEAMOC	331,357,688	1.34
	CONSMAT	111,150,947	0.45
	HOTRES	1,443,728,413	5.84
	TRANSCOM	1,478,319,278	5.98
	FIRE	1,938,330,979	7.84
	OTH	3,690,295,631	14.93
OTHERS	GOVERNMENT	1,045,683,959	4.23
	SAVING	7,633,174,070	30.88
TOTAL		**24,717,959,866**	**100.00**

Examining the trade data given in Table 5.10, in 2023, Türkiye's total imports (9.2 trillion TRY) exceeded exports (7.3 trillion TRY), reflecting a trade deficit (1.9 trillion TRY) driven by high dependence on imported intermediate goods. The country relies heavily on imports in the CONSMAT (16%), OTHMAN (14%), CHE (13%), MIN (12%) sectors, reflecting a strong dependence on imported inputs for production. Conversely, the main exporting sectors are OTH (17%), OTHMAN (15%) and TRANSCOM (13%), highlighting the dominance of manufacturing and service activities in the country's exports.

As for other key macroeconomic indicators, GDP at market prices, calculated as the sum of private consumption, public expenditure, gross investment and net exports (exports minus imports), was recorded at 27,091,469,065 kTRY in 2023.

Furthermore, the trade-to-GDP ratio, calculated as the sum of imports and exports relative to GDP at market prices, reached 61% in 2023. This notably high ratio demonstrates that Türkiye is a highly open economy, reflecting its strong integration with global markets and the pivotal role of external trade in driving economic growth. Lastly, the recurrent fiscal balance amounted to 1,737,298,161 kTRY, equivalent to approximately 6% of GDP at market prices, indicating that the Turkish government recorded a recurrent fiscal surplus in 2023.

Table 5.10. Sectoral exports and imports and their shares in 2023

Sectors	Exports (kTRY)	Export share (%)	Imports (kTRY)	Import share (%)
AGRF	189,494,189	2.60	308,647,644	3.35
MIN	81,027,789	1.11	1,079,946,856	11.73
FODPR	412,816,981	5.66	300,278,566	3.26
TEXCLOT	600,952,670	8.23	245,236,181	2.66
RPETR	272,470,124	3.73	666,043,500	7.24
CHE	582,964,171	7.99	1,191,847,738	12.95
MACHEQ	675,851,117	9.26	920,229,103	10.00
ELECTRO	408,869,087	5.60	846,406,783	9.20
OTHMAN	1,085,438,957	14.87	1,290,735,282	14.02
ELECSTEAMOC	4,869,320	0.07	12,335,539	0.13
CONSMAT	641,582,152	8.79	1,470,471,452	15.98
HOTRES	59,794,854	0.82	35,457,417	0.39
TRANSCOM	958,776,119	13.13	129,587,007	1.41
FIRE	92,757,253	1.27	104,508,163	1.14
OTH	1,231,763,531	16.87	601,645,213	6.54
TOTAL	**7,299,428,314**	**100.00**	**9,203,376,442**	**100.00**

5.8. Balancing the GEOSAM

The construction of SAM for a recent year in an efficient and cost-effective manner, while integrating information from different data sources, requires rigorous work by researchers (Robinson et al., 2001). The data compilation and statistical procedures vary significantly across datasets, including national income accounts, I-O tables, census data and surveys. Consequently, the final SAM requires careful validation, as inconsistencies may emerge due to differences in definitions across accounts and potential measurement errors (Thorbecke, 2000; Xie, 2000). Variations in data

compilation periods can also be another source of inconsistency, as I-O data are generally published every five years or at longer intervals, while national data on income, production and trade are reported annually (Lemelin et al., 2013). For Türkiye, the most recent I-O table refers to 2023 and was published in 2025, whereas the previous table covered 2012 and was released in 2016. The nine-year gap between the publication dates suggests that the intervals between I-O table releases can be considerably longer than the commonly cited five-year period, underscoring the challenges of conducting longitudinal analyses and maintaining temporal consistency when relying on such datasets.

In this study, the GEOSAM is established based on some sectoral aggregations and the integration of various administrative data, such as the balance of payments statistics, government revenue and expenditure data and social security institution statistics, in addition to the I-O Table. As a result, the equality between the sums of rows and columns is not satisfied, leading to an initially unbalanced SAM. Thus, several techniques such as the RAS method, cross-entropy method, Least Squares Adjustment and optimization models can be employed to balance the initial GEOSAM.

Among these techniques, the RAS method is applied when a consistent SAM for a specific period is updated for a later period by utilizing the new information and row and column totals without information on the flows within the SAM. In this method, each row is multiplied by a positive constant to equal the row totals to the target row totals, which will also lead to a change in column totals. After a similar multiplication process is implemented also for columns to attain target column totals, this sequence of row and column multiplication as an iterative approach continues until the convergence of both the column and row totals to the target vectors is achieved within an acceptable level of accuracy (Ahmed & Preckel, 2007). In a sense, RAS is a method for updating a SAM given known row and column totals. Unlike the RAS method primarily adjusting row and column sums, the cross-entropy method takes into consideration errors in variables, inequality constraints and prior knowledge about the SAM (Robinson, et al., 2001). In this way, the cross-entropy method utilizes all new information such as row and column sums, certain economic

aggregates such as total value-added, final demand components and/or imports to derive a new set of coefficients close to the prior and adjust them accordingly (Bwanakare, 2017). Similar to the cross-entropy approach, but formulated more generally as a quadratic form, the Least Squares method focuses on minimizing the difference between an a priori SAM and a posteriori matrix which fully satisfies all predefined constraints (Lemelin et al., 2013).

In this study, GEOSAM is balanced using a non-linear optimization model based on a synthesis of the RAS and least squares methods, following the approach proposed by Kılınç (2022). This model aims to find the row and column multipliers defined for intermediate flows that minimize the sum of squares of deviations between row and column sums, where total intermediate demand for 2023 is reported as 27,707,496,957 kTRY.

The optimization model for balancing GEOSAM is as follows:

$$Minimize \ \sum_{i \in I} vDev(i)^2 \tag{3}$$

$$s.t.$$

$$vTotR(i) = \sum_{j \in J} SAM(i,j) + \sum_{j \in setA \mid i \in setC} SAM(i,j) * [\, vR(i) * vC(j) \ - 1 \,] \quad \forall\, i \in I \tag{4}$$

$$vTotS(j) = \sum_{i \in I} SAM(i,j) + \sum_{i \in setC \mid j \in setA} SAM(i,j) * [\, vR(i) * vC(j) \ - 1 \,] \quad \forall\, j \in J \tag{5}$$

$$vDev(i) = vTotR(i) - vTotC(i) \quad \forall\, i \in I \tag{6}$$

- vR(i) and vC(j) are the row and column multipliers, respectively.
- vTotR(i) and vTotC(j) corresponds to row and column sums, respectively.
- vDev(i) is the difference between rows and column sums.
- Set A and Set C represent the set of activities and commodities, respectively.
- The indices i and j represent all SAM row and columns, respectively, including activities, commodities and other accounts, while I and J denote the corresponding index sets.

This optimization model is executed by using the GAMS IDE (General Algebraic Modelling System-Integrated Development Environment) and its solver CONOPT,

giving a balanced version of the initial GEOSAM. Indeed, the GAMS IDE is a software environment that provides a programming editor, allowing users to create input files, execute models and visualize results.

After balancing the GEOSAM, this study further disaggregates the electricity sector using detailed supplementary data sources. In doing so, it contributes to the literature on electricity-based SAM for Türkiye, where only a limited number of studies have employed self-constructed and electricity sector-disaggregated SAMs based on recent data, such as those developed by Bayar and Varoglu (2022) and Ipek (2023).

5.9. Further Disaggregation and Rebalancing the GEOSAM

As previously discussed, one of the main aims of this study is to examine alternative scenarios based on different electricity generation sources. Therefore, further disaggregation of the "Electricity, gas, steam and air conditioning supply" sector in the balanced GEOSAM is essential to enable a more detailed analysis of the electricity sector, particularly with respect to geothermal energy.

Table 5.11. NACE section D (Division 35): group and class descriptions

35	**Electricity, Gas, Steam and Air Conditioning Supply**		
	35.1	**Electricity**	Electric power generation, transmission and distribution
		35.11	Production of electricity
		35.12	Transmission of electricity
		35.13	Distribution of electricity
		35.14	Trade of electricity
	35.2	**Gas**	Manufacture of gas, distribution of gaseous fuels through mains
		35.21	Manufacture of gas
		35.22	Distribution of gaseous fuels through mains
		35.23	Trade of gas through mains
	35.3	**Steam**	Steam and air conditioning supply
		35.30	Steam and air conditioning supply

As given in Table 5.11, the "Electricity, gas, steam and air conditioning supply" sector consists of three subgroups: "Electricity", "Steam" and "Gas". Based on the

data sources and studies presented in this section, the final weights used for disaggregating these three groups are reported in Table 5.12. In addition to disaggregating the electricity sector from other two, by applying the disaggregation of the geothermal sector as ELECGEO and STEAMGEO, the impacts of exogenous shocks on both geothermal electricity and geothermal steam (heat) sectors can be revealed individually.

Table 5.12. Final weights for the disaggregation of "Electricity", "Steam" and "Gas" subgroups

Electricity (0.8770)	**Composition**	**Capital**	**Labor**	**Steam (0.0007)**	**Composition**	**Capital**	**Labor**	**Gas (0.1222)**	**Composition**	**Capital**	**Labor**
ELECBIO	0.03	0.06	0.02	STEAMGEO	0.48	0.48	0.48	GAS	1	1	1
ELECHYD	0.20	0.39	0.52	STEAMOTH	0.52	0.52	0.52				
ELECGEO	0.03	0.03	0.08								
ELECSOL	0.06	0.08	0.03								
ELECWND	0.11	0.11	0.06								
ELECOTH	0.58	0.34	0.29								

Starting the calculation of each cell in Table 5.12, the main weights for the "Electricity", "Steam" and "Gas" groups are calculated based on the "Production Value by Economic Activities, 2023" table published by TurkStat. As shown in Table 5.13, the electricity sector accounts for 87.7% of total production value, while the corresponding shares of the gas and steam sectors are approximately 12.2% and 0.1%, respectively.

Table 5.13. Weights of production values for "Electricity", "Steam" and "Gas" subgroups

NACE groups	**Production values (TRY)**	**Weights**
35.1 Electric power generation, transmission and distribution	2,255,861,620,864	0.8770
35.2 Manufacture of gas; distribution of gaseous fuels through mains	314,412,394,465	0.1222
35.3 Steam and air conditioning supply	1,831,947,961	0.0007
Total	**2,572,105,963,290**	**1**

Source: TurkStat (2024b)

The "Electricity" sector is further disaggregated into different electricity generation sources, including renewables such as biomass, hydro, geothermal, solar and wind,

as well as thermal options, namely coal and natural gas. The weights assigned to these energy sources are calculated based on their respective contributions to electricity generation, as reported in Table 5.14. The results indicate that in 2023, electricity generation in Türkiye was dominated by coal and natural gas, which together accounted for 58% of total generation. Among the renewable sources, hydro and wind made the largest contributions, with shares of 20% and 11%, respectively. On the other hand, geothermal energy accounted for 3% of total electricity generation.

Table 5.14. Weights of energy sources in electricity generation

Energy source	Electricity generation (MWh)	Weights
ELECBIO	9,706,500	0.03
ELECHYD	63,854,222	0.20
ELECGEO	10,997,593	0.03
ELECSOL	18,606,601	0.06
ELECWND	34,069,728	0.11
ELECOTH	186,854,427	0.58
TOTAL	**324,089,070**	**1.00**

Source: EMRA (2024)

For the disaggregation of the "Steam" sector into geothermal steam and steam from other sectors, labelled STEAMGEO and STEAMOTH, heat data from the "2023 National Energy Balance" table published by the MENR are utilized. The figures in Table 5.15 indicate that the geothermal sector has a remarkable share in heat generation.

Table 5.15. Weights of geothermal and other sectors in heat generation

Source	Heat generation (TJ)	Weights
Geothermal	118,908	0.48
Other Sectors	126,570	0.52

Source: MENR (2024b)

To assign the weights for the "Capital" of the "Electricity" sector, the study of Calikoglu and Koksal (2023) is taken as a reference for capital costs of different

energy technologies, especially for the Turkish context, after validating the consistency of these values by applying additional data sources. Subsequently, the capital cost values are adjusted by multiplying the installed electricity capacity of each energy technology, included in the EMRA Electricity Market Sector Report 2023. As shown in Table 5.16, hydro and thermal sources stand out with their higher capital cost weights compared to other energy technologies. Although geothermal power has relatively high capital costs per MW, its estimated capital weight remains low because geothermal represents only a small share of Türkiye's total installed electricity capacity in 2023.

Table 5.16. Calculation of the capital weights for different energy technologies

Energy technology	Capital costs (thousand USD/MW) (A)	Total installed electricity capacity in 2023 (MW) (B)	A*B	Weights based on A*B
ELECBIO	4,078	2,080	8,483,871	0.06
ELECHYD	1,870	31,962	59,769,052	0.39
ELECGEO	2,772	1,691	4,688,394	0.03
ELECSOL	827	13,998	11,576,553	0.08
ELECWND	1,446	11,807	17,072,199	0.11
ELECOTH	1,090	47,542	51,821,129	0.34

Source: Based on Calikoglu and Koksal (2023) and EMRA (2024)

To calculate the labor weights for the "Electricity" sector, data on renewable energy employment in Türkiye for 2018 and 2023 are obtained from SHURA (2021) and the IRENA (2025b), respectively. Furthermore, in the CAN (2021), the number of employees in the coal, gas and renewable-based electricity generation sectors in 2018 is estimated at 8,000, 4,000 and 35,000, respectively. Similarly, installed electricity capacity data for 2018 and 2023 are taken from the EMRA Electricity Market Sector Reports. Firstly, the employment data for coal and gas sectors are derived for 2023 by extrapolating the 2018 employment data based on changes in their installed capacities. After reviewing the IRENA-based employment data, which include all renewable energy sectors beyond electricity generation, it is concluded that directly using these figures for electricity generation sector may be misleading, particularly

for the solar sector, as they also capture a substantial number of manufacturing jobs. Therefore, using the operation, maintenance and repair cost weight for the solar sector (0.014) reported in the Solar3GW (2024) study and the total solar employment data for 2018, the number of employees in the solar electricity generation sector is estimated at 549. This value is then extrapolated using installed capacity data for 2018 and 2023 to obtain the corresponding solar employment for 2023. For other renewable energy technologies, a ratio such as employment in the renewable electricity sector (34,451) to employment in all renewable sectors (61,600) is calculated as 0.559 for 2018 and by using this ratio the 2023 electricity sector employment data is approximated also for the renewable technologies other than solar. Finally, the calculated 2023 labor shares of all energy technologies for the electricity generation sector are presented in Table 5.17.

Table 5.17. Calculation of the labor weights for different energy technologies

Energy technology	2018 Labor data	2023 Labor data	Installed electricity capacity in 2018 (MW)	Installed electricity capacity in 2023 (MW)	Estimated 2023 labor data for the electricity generation sector	Estimated 2023 labor weights for the electricity generation sector
BIO	1,200	1,200	670	2,080	671	0.02
HYD	47,700	40,968	28,293	31,962	22,912	0.52
GEO	6,000	5,960	1,283	1,691	3,333	0.08
WND	6,700	5,100	6,994	11,807	2,852	0.06
SOL	39,200	62,244	5,099	13,998	1,507	0.03
Total RE employment (excl. SOL)	61,600					
RE employment in the electricity sector	35,000					
RE employment in electricity sector (excl. SOL)	34,451					
RE employment in electricity sector ratio (excl. SOL)	0.559					
COAL	8,000		19,557	21,814	8,923	0.20
GAS	4,000		25,885	25,729	3,976	0.09

Source: EMRA (2019), CAN (2021), SHURA (2021), EMRA (2024), Solar3GW (2024) and IRENA (2025b)

For the capital and labor weights of the steam sector, the weights previously calculated from heat generation data are employed as proxies due to data limitations.

To more consistently reflect the linkages between sectors and energy technologies in the final SAM, sectoral cost structures compiled and validated from various studies, as presented in Table 5.18, are also taken into account. According to these figures, the construction sector accounts for 45% of the total investment expenditures of the geothermal sector, while the corresponding shares for mining, machinery and equipment and other sectors are 15%, 10% and 30%, respectively.

Table 5.18. Sectoral weights for cost structures of different energy technologies

Sectors	ELECBIO	ELECHYD	ELECGEO	ELECSOL	ELECWND	ELECOTH
AGRF	0.500	0.000	0.000	0.000	0.000	0.000
MIN	0.000	0.000	0.150	0.000	0.000	0.500
FODPR	0.000	0.000	0.000	0.000	0.000	0.000
TEXCLOT	0.000	0.000	0.000	0.000	0.000	0.000
RPETR	0.000	0.000	0.000	0.000	0.000	0.375
CHE	0.125	0.000	0.000	0.000	0.120	0.125
MACHEQ	0.000	0.250	0.100	0.350	0.490	0.000
ELECTRO	0.000	0.140	0.000	0.175	0.060	0.000
OTHMAN	0.000	0.000	0.000	0.000	0.000	0.000
CONS	0.250	0.180	0.450	0.300	0.260	0.000
HOTRES	0.000	0.000	0.000	0.000	0.000	0.000
TRANSCOM	0.000	0.000	0.000	0.000	0.000	0.000
FIRE	0.000	0.000	0.000	0.000	0.000	0.000
OTH	0.125	0.430	0.300	0.175	0.070	0.000

Source: Author's compilation based on Pollin et al. (2015) and Garrett-Peltier (2017)

Following the disaggregation of the electricity, gas, steam and air conditioning supply sector using the weights reported in Table 5.12, the GEOSAM is further rebalanced to eliminate any potential inconsistencies arising from the disaggregation process. The final GEOSAM, presented in Table 5.19, serves as the primary database for the SAM multiplier analysis and CGE modelling in this study.

Table 5.19. Final GEOSAM

	(Billion TRY)	ACTIVITIES: AGRF	MIN	FODPR	TEXCLOT	RPETR	CHE	MACHEQ	ELECTRO	OTHMAN	ELECBIO	ELECHYD	ELECGEO	ELECSOL	ELECWND	ELECOTH	STEAMGEO	STEAMOTH	GAS	CONSMAT	HOTRES	TRANSCOM	FIRE	OTH
ACTIVITIES	AGRF																							
	MIN																							
	FODPR																							
	TEXCLOT																							
	RPETR																							
	CHE																							
	MACHEQ																							
	ELECTRO																							
	OTHMAN																							
	ELECBIO																							
	ELECHYD																							
	ELECGEO																							
	ELECSOL																							
	ELECWND																							
	ELECOTH																							
	STEAMGEO																							
	STEAMOTH																							
	GAS																							
	CONSMAT																							
	HOTRES																							
	TRANSCOM																							
	FIRE																							
	OTH																							
COMMODITIES	AGRF	423.32	2.33	875.05	64.04	0.02	13.08	1.39	0.20	48.11	1.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.35	34.40	32.96	27.41	1.37	47.21
	MIN	4.60	73.11	6.35	5.48	539.77	21.78	14.49	4.02	15.03	0.00	0.00	34.94	0.00	0.00	406.64	0.22	0.23	78.17	306.40	2.06	48.77	1.08	36.08
	FODPR	64.82	1.92	478.89	12.80	0.46	10.41	6.69	1.34	13.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.47	54.47	245.76	20.82	5.36	97.33
	TEXCLOT	1.18	1.07	3.12	690.98	0.07	10.99	9.60	1.92	42.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	21.94	7.30	9.33	1.93	58.84
	RPETR	35.50	13.66	6.04	3.61	21.45	47.81	10.25	2.97	11.86	0.00	0.00	0.00	0.00	0.00	7.95	0.01	0.01	2.04	151.46	5.87	413.99	2.34	270.44
	CHE	137.83	15.08	74.93	160.94	5.36	806.91	93.71	85.40	244.13	0.91	0.00	0.00	0.00	1.48	1.35	0.00	0.00	1.04	224.63	15.81	45.44	20.21	157.58
	MACHEQ	0.69	9.51	8.32	9.84	0.86	21.13	222.43	33.28	146.62	0.00	2.57	0.37	3.61	7.13	0.00	0.00	0.00	1.23	212.32	5.79	19.14	6.73	440.97
	ELECTRO	0.58	2.24	3.79	4.84	0.49	5.58	42.23	154.93	72.30	0.00	3.07	0.00	3.85	1.86	0.00	0.01	0.01	2.62	84.79	5.86	21.73	6.62	389.58
	OTHMAN	8.59	7.41	29.69	36.95	2.00	41.50	82.92	42.47	618.82	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.35	157.34	16.26	101.30	19.87	344.80
	ELECBIO	0.41	0.65	0.97	1.74	0.30	0.92	0.97	0.31	1.54	0.83	6.56	0.40	1.92	4.96	23.86	0.01	0.01	4.54	5.64	0.86	1.08	5.15	4.98
	ELECHYD	2.71	4.29	6.35	11.43	2.00	6.08	6.39	2.06	10.11	5.49	43.17	2.65	12.62	32.61	156.99	0.08	0.09	29.84	37.13	5.64	7.12	33.86	32.74
	ELECGEO	0.47	0.74	1.09	1.97	0.35	1.05	1.10	0.35	1.74	0.95	7.43	0.46	2.17	5.62	27.04	0.01	0.02	5.14	6.40	0.97	1.23	5.83	5.64
	ELECSOL	0.79	1.25	1.85	3.33	0.58	1.77	1.86	0.60	2.95	1.60	12.58	0.77	3.68	9.50	45.74	0.02	0.03	8.70	10.82	1.64	2.08	9.87	9.54
	ELECWND	1.45	2.29	3.39	6.10	1.07	3.24	3.41	1.10	5.40	2.93	23.03	1.41	6.73	17.40	83.76	0.04	0.05	15.92	19.81	3.01	3.80	18.07	17.47
	ELECOTH	7.93	12.55	18.58	33.46	5.86	17.79	18.70	6.01	29.59	16.07	126.32	7.74	36.92	95.44	459.39	0.25	0.26	87.32	108.67	16.51	20.84	99.09	95.79
	STEAMGEO	0.01	0.01	0.01	0.02	0.00	0.01	0.01	0.00	0.02	0.01	0.09	0.01	0.03	0.07	0.31	0.00	0.00	0.06	0.07	0.01	0.01	0.07	0.07
	STEAMOTH	0.01	0.01	0.01	0.02	0.00	0.01	0.01	0.00	0.02	0.01	0.09	0.01	0.03	0.07	0.33	0.00	0.00	0.06	0.08	0.01	0.02	0.07	0.07
	GAS	1.92	3.03	4.49	8.09	1.42	4.30	4.52	1.45	7.15	3.88	30.54	1.87	8.92	23.07	111.05	0.06	0.06	21.11	26.27	3.99	5.04	23.95	23.16
	CONSMAT	5.96	22.02	14.02	10.76	1.07	40.21	583.37	234.57	420.07	4.33	3.73	3.32	6.23	7.62	0.00	0.01	0.01	2.47	2,242.01	11.72	28.28	48.45	256.74
	HOTRES	0.14	0.95	1.89	1.88	0.08	1.21	3.08	0.82	4.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15	16.52	37.46	9.36	5.57	146.28
	TRANSCOM	27.42	30.09	89.53	45.95	17.60	59.20	77.02	35.82	149.91	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	4.82	279.00	34.42	843.65	34.75	667.26
	FIRE	7.09	19.72	40.62	40.16	4.44	31.12	44.63	21.88	70.71	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	8.08	136.65	51.58	166.76	468.07	706.29
	OTH	131.30	58.63	391.66	237.85	29.64	197.51	234.62	151.76	503.73	16.44	67.58	16.78	27.59	15.58	0.00	0.05	0.06	18.77	1,159.48	226.55	604.17	303.35	1,243.69
	LABOR	72.83	79.53	207.39	320.95	41.40	191.81	293.53	122.71	374.78	0.85	28.89	4.20	3.60	3.50	16.57	0.02	0.02	8.03	647.59	346.62	409.71	314.48	4,266.49
	CAPITAL	1,629.41	210.76	590.69	413.17	93.70	445.13	493.65	229.56	802.70	20.70	145.82	11.44	28.24	41.65	126.43	0.15	0.16	52.17	1,346.49	588.15	2,001.59	2,102.19	4,964.36
	HOUSEHOLD																							
	GOVERNMENT																							
	CAPACC																							
	RoW																							

	(Billion TRY)	COMMODITIES: AGRF	MIN	FODPR	TEXCLOT	RPETR	CHE	MACHEQ	ELECTRO	OTHMAN	ELECBIO	ELECHYD	ELECGEO	ELECSOL	ELECWND	ELECOTH	STEAMGEO	STEAMOTH	GAS	CONSMAT	HOTRES	TRANSCOM	FIRE	OTH	LABOR	CAPITAL	HOUSEHOLD	GOVERNMENT	CAPACC	RoW
ACTIVITIES	AGRF	2,377.46																									922.41	0.00	145.25	189.49
	MIN		491.80																								76.50	7.56	38.08	81.03
	FODPR			2,445.91																							2,269.43	0.00	-183.80	412.82
	TEXCLOT				1,525.43																						1,026.84	0.00	-44.43	600.95
	RPETR					497.54																					322.96	0.00	76.73	272.47
	CHE						1,397.60																				407.48	129.39	110.68	582.96
	MACHEQ							1,574.74																			81.64	0.00	1,660.60	675.85
	ELECTRO								726.68																		503.01	0.00	494.06	408.87
	OTHMAN									2,512.63																	1,435.63	6.08	1,586.22	1,085.44
	ELECBIO										76.10																8.70	0.00	0.00	0.13
	ELECHYD											500.62															57.26	0.00	0.00	0.84
	ELECGEO												86.22														9.86	0.00	0.00	0.14
	ELECSOL													145.88													16.68	0.00	0.00	0.25
	ELECWND														267.11												30.55	0.00	0.00	0.45
	ELECOTH															1,464.96											167.56	0.00	0.00	2.46
	STEAMGEO																1.00										0.11	0.00	0.00	0.00
	STEAMOTH																	1.06									0.12	0.00	0.00	0.00
	GAS																		354.14								40.50	0.00	0.00	0.60
	CONSMAT																			6,648.81							111.15	0.07	4,215.25	641.58
	HOTRES																				1,607.01						1,443.73	0.00	0.00	59.79
	TRANSCOM																					3,853.90					1,478.32	52.17	114.99	958.78
	FIRE																						3,445.57				1,938.33	10.42	0.00	92.76
	OTH																							13,051.61			3,690.30	3,380.16	1,156.84	1,231.76
COMMODITIES	AGRF																													
	MIN																													
	FODPR																													
	TEXCLOT																													
	RPETR																													
	CHE																													
	MACHEQ																													
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	STEAMGEO																													
	STEAMOTH																													
	GAS																													
	CONSMAT																													
	HOTRES																													
	TRANSCOM																													
	FIRE																													
	OTH																													
	LABOR																									7,735.52	16,338.31		619.50	4.64
	CAPITAL																													
	HOUSEHOLD																													
	GOVERNMENT	-45.95	149.62	354.44	72.75	243.38	150.83	399.80	230.98	735.83	0.91	5.96	1.03	1.74	3.18	17.45	0.01	0.01	4.22	154.13	31.52	58.45	216.53	210.84				1,045.68		2,029.76
	CAPACC																											7,633.17	1,737.30	
	RoW	308.65	1,079.95	300.28	245.24	666.04	1,191.85	920.23	846.41	1,290.74	0.32	2.13	0.37	0.62	1.14	6.24	0.00	0.00	1.51	1,470.47	35.46	129.59	104.51	601.65					130.45		

5.10. Development of Alternative Scenarios for SAM Multiplier Analysis

This study examines the impacts of various exogenous shocks, where government, investment and exports are assumed to be exogenous components of final demand. The analysis focuses on two main groups of scenarios and, for simplicity, employs the unconstrained SAM multiplier approach, assuming unlimited supply capacity across all sectors to meet increased demand.

The first part of the scenarios examines the direct, indirect and induced effects of a one-unit increase in commodity demand resulting from an exogenous shock across sectors. For the electricity sector, a one-unit increase in electricity demand is assumed to be met by a corresponding one-unit increase in electricity generation. In alternative scenarios, this additional electricity demand is assumed to be supplied exclusively by a single energy resource such as solar, geothermal, or wind, allowing the impacts of a one-unit increase in generation from each resource to be evaluated separately. Furthermore, an additional scenario (ALL ELECTRICITY) is considered in which the one-unit increase in electricity demand is met using the electricity generation mix observed in 2023, as reported in Table 5.14.

The second part of the scenarios focuses on the impacts of investing in different electricity generation technologies to increase 2023 electricity production by 1% in order to meet rising electricity demand. As given in Table 5.14, electricity generation in 2023 is 324,089,070 MWh and its 1% corresponds to 3,240,891 MWh. Then, the installed capacity required to generate this amount of electricity solely from each individual energy technology is calculated based on their respective capacity factors. Following this calculation, the installed capacity values are multiplied by their capital costs. Taking hydropower, the most expensive option, as the reference, the units of investment in other energy technologies that could be installed with the same level of investment cost is calculated. Indeed, these comparative investment values constitute the main inputs used in the SAM multiplier analysis. All of these computations are presented in Table 5.20.

Based on the figures in Table 5.20, geothermal energy stands out as having the highest capacity factor in 2023, highlighting its role as a reliable baseload. Other

renewable sources, with capacity factors ranging from 15% to 53% and thermal sources at around 45% lag behind geothermal. This comparative advantage in capacity factor implies that geothermal requires less installed capacity investment to generate the same amount of electricity. However, geothermal and biomass technologies continue to exhibit comparatively high capital costs relative to other renewable resources. When total capital requirements are taken into account, it follows that, in place of 1 unit (MW) of hydropower, the costliest alternative, investment could be directed toward 2.20 units of geothermal, 1.50 units of solar, or 3.38 units of thermal capacity.

Table 5.20. Derivation of electricity sector investment inputs used in the SAM multiplier scenarios[11]

Energy technology	Capacity factor in 2023	Installed capacity required (MW)	Capital costs (Thousand USD/MW)	Capital costs for installed capacity required (Thousand TRY/MW) in 2023	Units of new investment compared to hydropower
BIO	0.53	694.62	4,078	67,332,534	1.07
HYD	0.23	1,622.22	1,870	72,107,480	1.00
GEO	0.74	498.42	2,772	32,841,279	**2.20**
SOL	0.15	2,438.21	827	47,929,819	1.50
WND	0.33	1,123.10	1,446	38,602,406	1.87
OTH	0.45	824.60	1,090	21,364,712	3.38

5.10.1. Formulation of Geothermal Heat Generation Scenarios

In addition to geothermal electricity generation, this study also assesses the impacts of expanding geothermal heat generation capacity. In principle, geothermal heat can be supplied either directly through heat pumps or ground-coupled heat exchangers or indirectly by utilizing waste heat from electricity generation in combined heat and power (CHP) geothermal plants. In the scenario analyses conducted in this study, the primary focus is on the latter, i.e., the use of waste heat.

[11] The average exchange rate for 2023 is taken as 23.77. The capacity factor is defined as the ratio of actual electricity generated over a given period to the maximum possible output, calculated as installed capacity (MW) × 365 × 24.

Geothermal heat generation can depend on several factors, including plant size (directly related to heat demand in the region) and plant design, fluid temperature, reinjection strategy and other reservoir and operational characteristics. To illustrate, as given in the examples of high temperature CHPs in the study of Lund and Chiasson (2007), the Nesjavellir Power Plant in Reykjavik, Iceland, is located in a geothermal field with temperatures as high as 380 °C. With an installed capacity of 210 MWe, it can produce 2,100 GWh/yr of electricity at 190 °C and 4,500 TJ/yr (1,250 GWh/yr) of heat at 83 °C for district heating. These figures indicate that 0.60 units of heat are generated in addition to 1 unit of electricity generation for this specific plant. Similarly, Sudurnes Regional Heating Corporation plant at Svatsengi, Iceland, with 46.4 MWe installed capacity and 240 °C reservoir fluid could produce 370 GWh/yr electricity and 2,700 TJ/yr (750 GWh/yr) heat at 95-100 °C for district heating. This implies that 2.03 units of heat are generated in addition to 1 unit of electricity generation in this plant.

In addition to these international examples, this study incorporates insights from interviews with Turkish experts in the geothermal sector to better characterize the heat-generation potential of geothermal power plants in Türkiye. As a country endowed with abundant geothermal resources, Türkiye has geothermal power plants with reservoir temperatures reaching up to 242 °C. The geothermal fields, generating or capable of generating electricity in the country, are distributed across temperature ranges as follows: 2 fields below 140 °C, 3 in the 140-160 °C range, 3 in the 160-180 °C range, 1 in the 180-200 °C range and 4 above 200 °C, as reported in the study by Zaim and Çavşi (2018). In an example of a high-temperature CHP plant with an installed capacity of 80 MWe, the resource temperatures used for electricity generation and greenhouse heating are approximately 170°C and 105°C, respectively. The plant operates with a load factor of 95%. Under these conditions, Turkish experts indicate that the heat output of this plant could reach up to eight times its electricity generation.

Besides the heat generation potential of geothermal power plants, the costs associated with installing the heating systems should also be taken into account for investment-based analyses. In this context, the distribution network costs, which

cover the pipeline or cable infrastructure for transporting and distributing heat, together with the substation costs related to consumer installations, determine the overall heating system costs (Gudmundsson & Thorsen, 2013).

According to the ESMAP (2022) document, the capital expenditure (CAPEX) for geothermal heat production ranges from USD 20-35 million for a 50 MW plant, while the CAPEX for a district heating system, including distribution but excluding individual household heating installation, is estimated at USD 108-192 million for a 135 MW system. Taken together, these figures indicate that the additional per-MW investment required for distributing heat from a geothermal power plant can be up to twice the cost of heat generation itself. Similarly, the estimated cost of producing heat in geothermal district heating systems ranges from USD 800-1,420 per kW, while geothermal heat generation costs at the generation facility are reported to be USD 400-700 per kW. These cost estimates further confirm the roughly two-to-one ratio between heat distribution and heat generation. Indeed, this ratio is employed as a reference value for the cost component of this study.

In light of all this evidence, the geothermal heat generation potential is assumed to be 0.25, 1, 2, 5 times the electricity generation, while the heat distribution cost for a CHP, are taken as 1.5, 2 and 3 times that of a conventional geothermal power plant in the scenario analyses of this study.

Under these three cost assumptions, the comparative value for the geothermal power plant reported as 2.20 in Table 5.20 is integrated into GEOSAM as 1.46, 1.10 and 0.73, respectively, assuming that this plant now operates a district heating system. For example, when distribution costs for a CHP is 1.5 and heat generation potential is 0.25 units, the geothermal electricity generation cell takes a value of 1.46, while the geothermal heat generation cell equals 1.46 * 0.25, with all other cells in the shock matrix are set to zero.

Following the same approach, alternative combinations of geothermal heat and electricity generation are constructed for analytical purposes as given in Table 5.21.

Table 5.21. Geothermal inputs in SAM multiplier analyses based on heat generation potential and costs

Sector	0.25G & 1.5C	0.25G & 2C	0.25G & 3C	1G & 1.5C	1G & 2C	1G & 3C	2G & 1.5C	2G & 2C	2G & 3C	5G & 1.5C	5G & 2C	5G & 3C
ELEC GEO	1.46	1.1	0.73	1.46	1.1	0.73	1.46	1.1	0.73	1.46	1.1	0.73
STEAM GEO	0.37	0.27	0.18	1.46	1.1	0.73	2.92	2.2	1.46	7.3	5.49	3.65

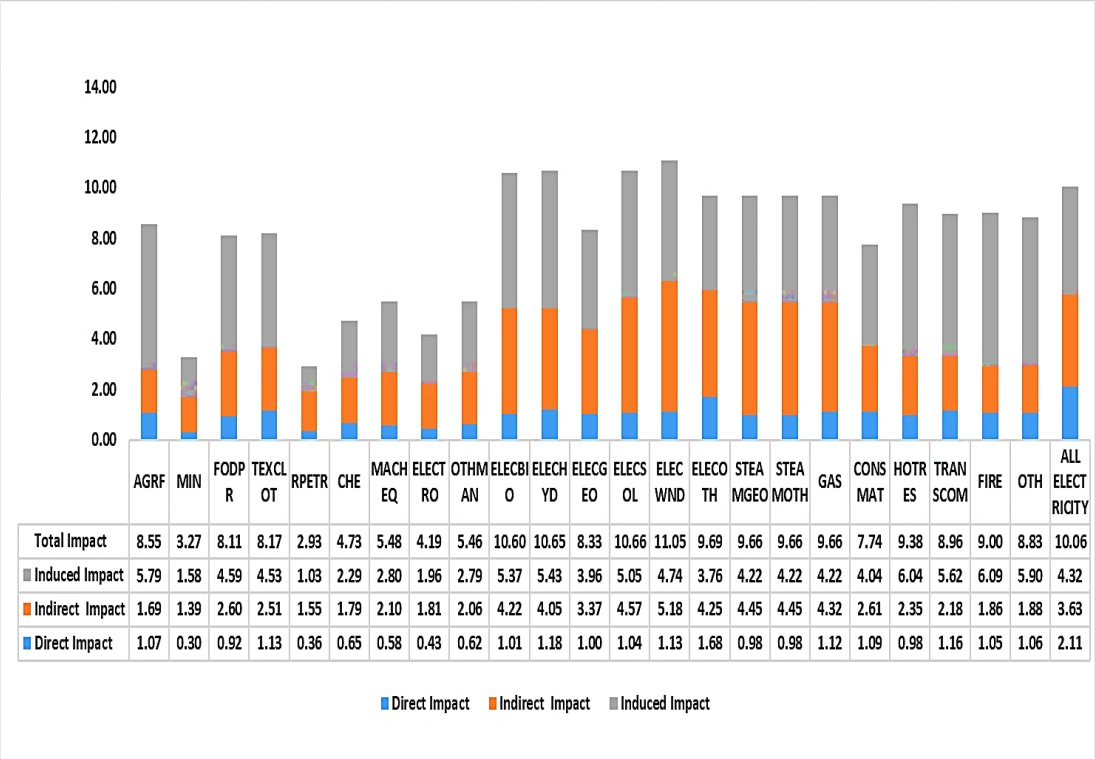
5.10.2. Results and Discussion of the SAM Multiplier Scenario Analysis

After specifying the exogenous shock matrices for Scenarios 1 and 2, the SAM multiplier analysis is conducted to assess the economy-wide effects of the proposed shocks.

Under the category of Scenario 1, assuming a one-unit increase in commodity demand due to an exogenous shock across sectors, the direct, indirect and induced impacts are presented in Figure 5.3. Considering sectoral direct impacts, the immediate effect of a one-unit increase in final demand on sectoral output is relatively higher in the ALL ELECTRICITY, ELECOTH, ELECHYD, TRANSCOM, TEXCLOT, ELECWND, GAS, CONSMAT, AGRF, OTH, FIRE, ELECSOL and ELECBIO sectors. In these sectors, the demand shock leads to a stronger direct impact, as the increase in final demand is largely satisfied by the sector's own production, resulting in more than a one-unit increase in output per one-unit increase in demand. Regarding the direct impacts within the electricity sector, meeting rising electricity demand, independent of the specific generation technology, leads to an overall expansion of the sector. This expansion is relatively stronger for hydro, wind and thermal energy technologies. In contrast, meeting this demand through the existing energy mix, rather than relying on individual technologies, as in the ALL ELECTRICITY scenario, generates an even stronger direct impact on the electricity sector.

In terms of indirect impacts, the commodity demand shock leads to notable increases in intermediate input requirements in several sectors, particularly ELECWND, ELECSOL, STEAMGEO, STEAMOTH, GAS, ELECOTH, ELECBIO, ELECHYD,

ALL ELECTRICITY, ELECGEO, CONSMAT, FODPR, TEXCLOT and HOTRES, indicating strong backward production linkages. On the other hand, regarding induced impacts, sectors such as FIRE, HOTRES, OTH, AGRF, TRANSCOM, ELECHYD, ELECBIO and ELECSOL emerge as the most prominent. In these sectors, a one-unit increase in final demand leads to an increase of more than five units in sectoral output, driven by rising factor incomes, higher institutional expenditures and the resulting feedback effects on the sectors' own production.

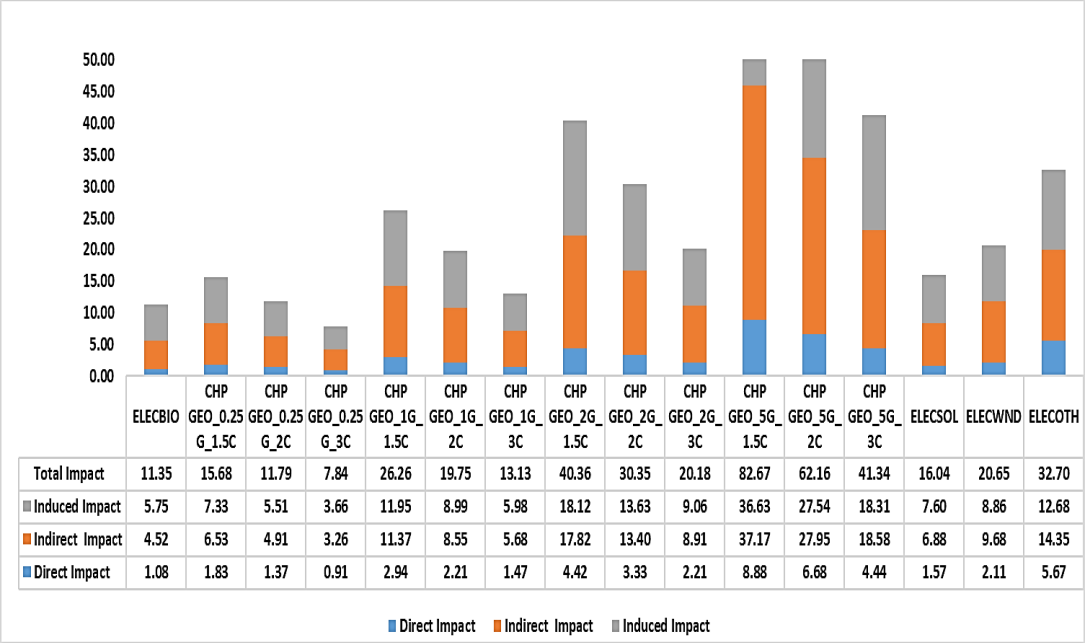


	AGRF	MIN	FODPR	TEXCLOT	RPETR	CHE	MACHEQ	ELECTRO	OTHMAN	ELECBIO	ELECHYD	ELECGEO	ELECSOL	ELECWND	ELECOTH	STEAMGEO	STEAMOTH	GAS	CONSMAT	HOTRES	TRANSCOM	FIRE	OTH	ALL ELECTRICITY
Total Impact	8.55	3.27	8.11	8.17	2.93	4.73	5.48	4.19	5.46	10.60	10.65	8.33	10.66	11.05	9.69	9.66	9.66	9.66	7.74	9.38	8.96	9.00	8.83	10.06
Induced Impact	5.79	1.58	4.59	4.53	1.03	2.29	2.80	1.96	2.79	5.37	5.43	3.96	5.05	4.74	3.76	4.22	4.22	4.22	4.04	6.04	5.62	6.09	5.90	4.32
Indirect Impact	1.69	1.39	2.60	2.51	1.55	1.79	2.10	1.81	2.06	4.22	4.05	3.37	4.57	5.18	4.25	4.45	4.45	4.32	2.61	2.35	2.18	1.86	1.88	3.63
Direct Impact	1.07	0.30	0.92	1.13	0.36	0.65	0.58	0.43	0.62	1.01	1.18	1.00	1.04	1.13	1.68	0.98	0.98	1.12	1.09	0.98	1.16	1.05	1.06	2.11

Figure 5.3. Sectoral direct, indirect and induced impacts of exogenous commodity demand shock (Scenario 1)

Examining the total impacts of a one-unit increase in commodity demand, sectors such as ELECWND, ELECSOL, ELECHYD, ELECBIO, ALL ELECTRICITY, ELECOTH, STEAMGEO, GAS, STEAMOTH, HOTRES, FIRE and TRANSCOM generate the largest aggregate economic impacts. Within the electricity sector, renewable technologies, namely wind, solar, hydro and biomass, stand out as generating the highest total impacts, while geothermal electricity generation lags behind these renewables as well as some thermal energy technologies. In contrast, geothermal heat generation appears among the sectors with the highest total impacts,

suggesting that geothermal energy can deliver stronger economy-wide effects when electricity and heat generation are jointly considered rather than electricity generation alone. This finding suggests that excluding geothermal heat generation from geothermal expansion scenarios may result in an underestimation of the full economic potential of this energy source. Thus, geothermal heat generation is incorporated into the subsequent scenarios of this study alongside electricity generation to more accurately capture the overall impact of geothermal energy development.



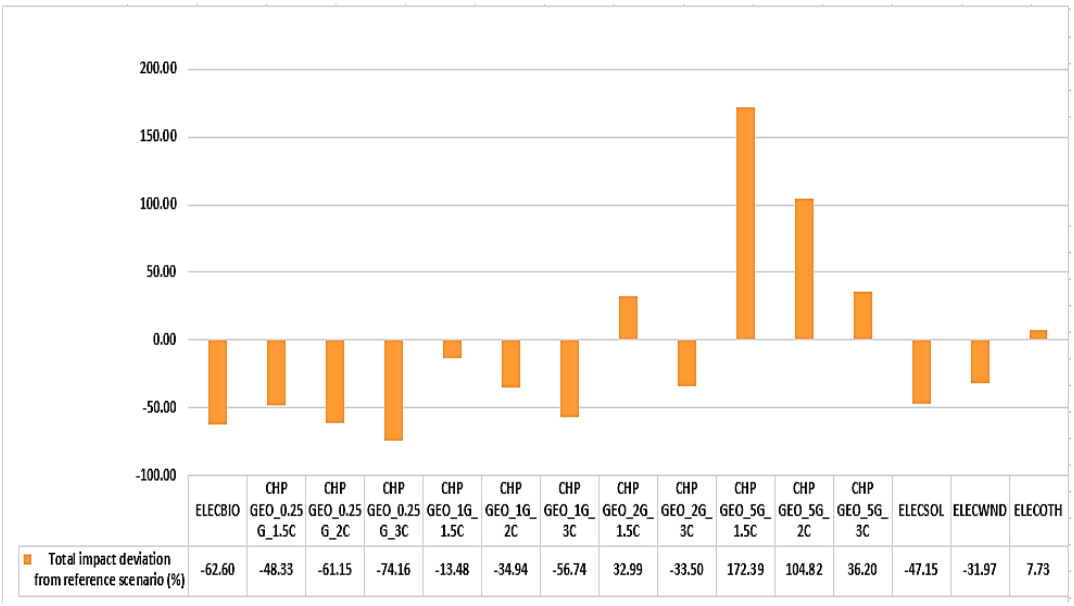
	ELECBIO	CHP GEO_0.25 G_1.5C	CHP GEO_0.25 G_2C	CHP GEO_0.25 G_3C	CHP GEO_1G_ 1.5C	CHP GEO_1G_ 2C	CHP GEO_1G_ 3C	CHP GEO_2G_ 1.5C	CHP GEO_2G_ 2C	CHP GEO_2G_ 3C	CHP GEO_5G_ 1.5C	CHP GEO_5G_ 2C	CHP GEO_5G_ 3C	ELECSOL	ELECWND	ELECOTH
Total Impact	11.35	15.68	11.79	7.84	26.26	19.75	13.13	40.36	30.35	20.18	82.67	62.16	41.34	16.04	20.65	32.70
Induced Impact	5.75	7.33	5.51	3.66	11.95	8.99	5.98	18.12	13.63	9.06	36.63	27.54	18.31	7.60	8.86	12.68
Indirect Impact	4.52	6.53	4.91	3.26	11.37	8.55	5.68	17.82	13.40	8.91	37.17	27.95	18.58	6.88	9.68	14.35
Direct Impact	1.08	1.83	1.37	0.91	2.94	2.21	1.47	4.42	3.33	2.21	8.88	6.68	4.44	1.57	2.11	5.67

Figure 5.4. Direct, indirect and induced impacts of electricity sector investments under geothermal heat generation (Scenario 2)

Under Scenario 2, the impacts of investing in alternative electricity generation technologies are evaluated relative to hydropower (10.65), with the highest investment requirement among the energy technologies, while also accounting for the investment costs and heat generation potential of geothermal CHP plants. As shown in Figure 5.4, thermal and high-heat-generation geothermal investments (5G) generate the largest direct impacts, while geothermal investments with high heat generation drive the highest indirect and induced impacts. Considering the total impacts across investment scenarios other than geothermal, wind technologies (20.65) and thermal technologies (32.70) stand out as generating the highest total

impacts. As suggested in the literature, a geothermal heat generation investment may require a two-unit cost while delivering two units of heat generation, along with a one-unit geothermal electricity generation plant investment, which also serves as the reference case for all other alternatives in Figure 5.4.

As seen in Figure 5.4., the total impact for this reference case is estimated at 30.35, exceeding the impact of wind energy investment and being comparable to that of thermal energy technologies. Moreover, a geothermal heat generation potential above 2.22 G results in a total impact greater than 32.70. Considering that geothermal plants in Türkiye may have heat generation potentials up to eight times greater than electricity output as confirmed by experts, the scenario with the highest cost (3C) and heat generation potential (5G) shows that geothermal systems integrating heat and electricity generate a total economic impact roughly twice that of the strongest renewable alternative, wind energy and about 1.3 times that of thermal energy.



	ELECBIO	CHP GEO_0.25G_1.5C	CHP GEO_0.25G_2C	CHP GEO_0.25G_3C	CHP GEO_1G_1.5C	CHP GEO_1G_2C	CHP GEO_1G_3C	CHP GEO_2G_1.5C	CHP GEO_2G_3C	CHP GEO_5G_1.5C	CHP GEO_5G_2C	CHP GEO_5G_3C	ELECSOL	ELECWND	ELECOTH
Total impact deviation from reference scenario (%)	-62.60	-48.33	-61.15	-74.16	-13.48	-34.94	-56.74	32.99	-33.50	172.39	104.82	36.20	-47.15	-31.97	7.73

Figure 5. 5. Comparison of total impacts of electricity sector investments under geothermal heat generation relative to the reference scenario (%)

Focusing specifically on the comparison between the reference scenario (CHP GEO_2G_2C) and the alternative geothermal scenarios shown in Figure 5.5, the total economic impact increases remarkably, by 33%, when the cost associated with heat generation is reduced, as in the 1.5C and 2G case (CHP GEO_2G_1.5C). On the

other hand, even when heat generation costs are high, a sufficiently large heat output can notably raise the total economic impact. In particular, the 3C and 5G case (CHP GEO_5G_3C) exceeds the reference scenario by 36%, indicating that high heat generation potential can offset higher costs. In a scenario where costs are reduced and heat generation is substantially increased, as in the 1.5C and 5G case (CHP GEO_5G_1.5C), the total economic impact exceeds that of the reference scenario by 172%, highlighting the significant potential of integrated investments in geothermal heat and electricity generation.

In line with the findings of Hartono et al. (2020a), which demonstrate that geothermal and wind power plants generate the highest economy-wide economic impacts in Indonesia, this study reaches similar conclusion for Türkiye, while extending the literature by highlighting the additional economic gains from incorporating geothermal heat generation. The results demonstrate that geothermal power investments can yield substantial economic benefits, balancing out the costs, particularly when integrated with heat generation. From a methodological perspective, these findings highlight the importance of incorporating geothermal heat generation into modelling studies. Unlike previous research, by jointly modelling geothermal electricity and heat generation, this study demonstrates that geothermal energy can provide benefits exceeding those of other energy sources. In addition to electricity generation, as underlined also by TÜBA (2020), it can support cross-sectoral synergy through its provision of thermal energy and create opportunities in agriculture, tourism, manufacturing and urban infrastructure. Moreover, beyond sectoral expansion and economic growth, the integrated use of geothermal energy can also generate social benefits for local communities, further distinguishing it from alternative energy sources.

Recently, geothermal energy associations and industry stakeholders have frequently emphasized the need for a JEKA model for geothermal energy, similar to the YEKA (Renewable Energy Resource Areas) mechanism that has been successfully implemented for large-scale wind and solar projects[12]. They have suggested that the

[12] Retrieved May 26, 2026, from https://kentege.com.tr/jeotermal-sektorunden-jeka-modeli-cagrisi/

model could initially be implemented in areas with geothermal potential identified by the MTA explorations., while promoting the integrated use of geothermal energy. JEKA auctions could encourage investors to integrate multiple geothermal applications within a single investment plan. Furthermore, similar to the YEKA mechanism, the JEKA model could also incorporate local content requirements, encourage the domestic production of critical equipment and support technology spill overs within the sector.

5.11. Conclusion and Policy Implications

As a country with substantial geothermal energy potential, Türkiye ranks among the world's leading countries in installed geothermal power capacity and direct-use applications. Over the past decade, the country has significantly expanded its installed capacity and accelerated the development of heating applications.

Although geothermal energy offers a wide range of direct-use applications, geothermal development in Türkiye has primarily followed an electricity-generation-oriented pathway similar to that of other renewable energy technologies. However, geothermal energy also has the potential to generate substantial economic and social benefits through the integrated use of heat and electricity. Despite being frequently acknowledged, providing clear and quantifiable evidence of these benefits is essential for informed policy decisions. Accordingly, this study quantitatively assesses the economic impacts of geothermal development and compares them with those of other energy sources.

Based on the SAM multiplier analysis for the Turkish case, this research evaluates the direct, indirect and induced impacts of an exogenous shock increasing commodity demand and electricity investments under two scenario categories. While examining sectoral responses to the shocks, the analysis focuses particularly on the electricity sector to assess the potential of geothermal energy to generate economic benefits relative to other energy sources. By applying a detailed and systematic disaggregation of the electricity sector, this study provides a robust methodological framework for energy-based SAM development, along with a reliable and consistent

dataset for future SAM-based modelling studies. In addition, the SAM constructed in this study captures both electricity and heat generation from geothermal energy, allowing for a more comprehensive and realistic representation of this energy source within the analytical framework. Furthermore, while primarily focusing on geothermal energy, this study adopts a comprehensive and multidimensional approach and provides a comparative assessment across multiple energy technologies.

Considering the effects of an exogenous commodity demand shock, it is evident that the electricity is one of the key sectors generating the largest economic impact in the economy, owing to its strong linkages and synergies with other sectors. This impact is particularly pronounced in the renewable electricity sector, highlighting the role of expanding renewable energy capacity in accelerating economic growth. Furthermore, the comparatively limited contribution of fossil energy resources to overall economy confirms that a growth strategy centred on renewable energy development can yield greater economic gains than continued dependence on conventional energy sources.

Evidence from electricity sector investment scenarios indicates that geothermal energy, when limited to electricity generation, exhibits relatively lower economic impacts compared to other energy resources. However, when geothermal power plant investments incorporate heat generation, geothermal energy is able to close this gap and, in some cases, surpass alternative technologies, owing to declining investment costs and increasing heat generation potential. In this way, geothermal energy can contribute to economic growth while reducing reliance on fossil fuels and mitigating carbon emissions, strengthening energy security.

The findings from this study underlines that investments in geothermal power plants should be designed to incorporate heat generation for direct use applications to fully exploit the economic potential of geothermal energy. At this point, introducing incentives for waste heat utilization in existing power plants or mandating combined heat and power applications in new geothermal projects as part of the licensing and permitting process would enhance resource efficiency and unlock the full geothermal potential of the country. Furthermore, building on Türkiye’s successful experience with

feed-in tariffs for power generation, which led to a significant increase in geothermal power plant investments, similar price-based support schemes or infrastructure incentives can be designed for heat generation. Such policies can ensure long-term revenue for project developers and promote the further development of geothermal heating applications.

Finally, SAM multiplier analysis in this study has some limitations. First, from a methodological perspective, the construction of the SAM involves several simplifying assumptions, including the exclusion of firms as a separate economic agent, the assumption of a single household and the partial treatment of the tax structure. Nevertheless, these assumptions do not undermine the analytical relevance of the model, as the GEOSAM is specifically designed to evaluate electricity-sector-based scenarios. Second, this study relies on a national SAM rather than an interregional one and therefore does not capture regional heterogeneity. In addition, the analysis assumes that all equipment is produced domestically and focuses solely on installed (capital) costs, excluding operational and maintenance costs. Third, the analysis draws on multiple data sources to disaggregate the SAM and to estimate the inputs used in the SAM multiplier scenarios based on geothermal heat potential and associated costs. However, the upfront costs of geothermal projects are highly site-dependent, driven by geographic location and resource characteristics. Consequently, differences in cost assumptions may affect the magnitude of the quantitative results across studies, while not necessarily altering the overall conclusions. Furthermore, beyond these constraints, SAM multiplier analysis has inherent limitations, including fixed prices, fixed Leontief production technology and the assumption of unlimited factor supplies. Thus, these limitations highlight the need for more advanced modelling approaches, such as a CGE model, which is employed in the following chapter of this thesis. Nevertheless, despite these drawbacks, the SAM multiplier analysis employed in this study offers valuable insights for policymakers assessing the economy-wide impacts of geothermal investments in comparison with other energy technologies and serves as a foundation for more advanced future research.

CHAPTER 6

ANALYZING GEOTHERMAL ENERGY DEVELOPMENT IN TÜRKİYE USING A COMPUTABLE GENERAL EQUILIBRIUM MODEL

This chapter presents the structural and mathematical framework of the CGE model developed in GAMS using the Mathematical Programming System for General Equilibrium (MPSGE) framework. First, an MPSGE-equivalent version of the base model, i.e., the algebraic CGE model (GeoCGE-TR), is constructed. Subsequently, the model is extended as GeoMPSGE-TR through the incorporation of appropriate nesting structures. During the interviews conducted within the scope of this thesis, stakeholders mainly attributed the development of the geothermal power sector in Türkiye to incentive mechanisms and emphasized their continued importance for future expansion. Building on these qualitative findings, the scenario analysis in this chapter examines the role of subsidies in supporting further geothermal capacity expansion and achieving Türkiye's long-term geothermal development targets.

6.1. CGE Models

General Equilibrium theory conceptualizes the economy as an interconnected system of economic agents making supply and demand decisions in pursuit of their own interests (Bryant, 2010). When producers maximize their profits and consumers maximize their utility, the interaction of these decisions leads to an economy-wide equilibrium in which quantities demanded and supplied are equal in all goods and factor markets (Blaug, 1992). In this way, the solution of a general equilibrium model consists of a vector of commodity and factor prices that simultaneously satisfy the quantity of supply and demand (Çırpıcı, 2008). General equilibrium models, grounded in microeconomic foundations, focus on the interrelations among different markets and sectors, as well as the behaviour of economic agents (Karadag, 1997).

From a mathematical perspective, general equilibrium is the solution of a linear or nonlinear optimization problem, in which an objective function is either maximized or minimized subject to specified constraints (Markusen, 2002).

Although the theoretical principles of general equilibrium were laid by Leon Walras in 1874, Computable General Equilibrium (CGE) modelling emerged with the formal proof of the existence of Walrasian general equilibrium by Arrow and Debreu (1954) and with Johansen's (1960) first multi-sectoral growth model. Building on Johansen's work, Scarf (1967) made a major contribution to CGE modelling by developing an algorithm for Arrow-Debreu-type economic models. The oil crises of the 1970s further accelerated the adoption of CGE models, as conventional econometric approaches failed to recognize oil prices as a key determinant of economic activity (Dixon & Parmenter, 1996). By the 1980s, these models began to gain widespread popularity as essential tools for analysing macroeconomic policies and resource allocation decisions in both developing and developed countries (Thissen, 1998). Furthermore, the improvements in data availability and computational tools also contributed to the steady growth of the CGE literature.

For CGE models, the term "*computable*" refers to the model's ability to quantify the economy-wide effects of a shock; "*general*" highlights the simultaneous representation of all economic activities in the economy; and "*equilibrium*" indicates a situation in which supply and demand are simultaneously determined at a set of prices (Burfisher, 2011). In a sense, the applied general equilibrium models aim to convert the Walrasian general equilibrium structure from an abstract representation of an economy into realistic models of actual economies (Shoven & Whalley, 1984, p. 1007). These models are regarded as "*the numerical implementation of general equilibrium models calibrated to data*" (Kehoe & Prescott, 1995, p.1). Unlike theoretical general equilibrium analysis, which emphasizes formal proofs of equilibrium existence and uniqueness, CGE models adopt a quantitative (numerical) approach to assess the impacts of policy changes or external and internal shocks on macroeconomic and sectoral structures (Bandara, 1991). Algebraically, once the supply and demand functions are derived from the optimization problems of consumers and firms, the general equilibrium problem is expressed as a system of n

equations in n unknowns (Markusen, 2002). Indeed, these equations incorporate the underlying optimizing behaviour of all economic agents. Solving this system yields the equilibrium values of the endogenous variables, conditional on the given exogenous parameters.

Considering the advantages of CGE models relative to SAM-based approaches, while a SAM provides a comprehensive representation of income and expenditure flows in an economy, a CGE model extends this framework by incorporating behavioural equations into the SAM's income and expenditure identities (Buehrer & di Mauro, 1993). In this context, although a SAM reports factor payments in the production process, it does not specify the underlying production technology, which is explicitly defined within the CGE models. Moreover, CGE models allow for the simultaneous analysis of both backward and forward effects of economic shocks and incorporate price adjustments that ensure economy-wide balance, whereas SAM multiplier analysis typically captures backward linkages under constant prices (Alkan, 2018). By including all sectors, the CGE models avoid the omission bias that arises in partial equilibrium models and the specification of nonlinear utility and production functions allows for a more accurate depiction of the real economy (Mukherjee, 1995). Indeed, widespread use of the CGE modelling approach in policy analysis stems from its ability to capture both direct and indirect effects of policy shocks, its strong theoretical and microeconomic foundation, its consistency within a general equilibrium framework and its capacity to quantify sectoral and aggregate welfare impacts (Ghaith et al., 2021).

6.1.1. Design and Formulation of CGE Models

CGE models can be designed within either a static or a dynamic framework. While static models mainly focus on how an economy adjusts from one set of exogenous conditions to another within a single period through comparative static analysis, dynamic CGE models allow policy impacts to be analysed across multiple time periods by incorporating the time dimension into the analyses (Iqbal & Siddiqui, 2001). In this sense, static models consider only the difference between the initial and the new equilibrium, without accounting for the adjustment process or transition

path followed by the economy between these equilibrium states, unlike dynamic models (Narayan & Prasad, 2007). On the other hand, dynamic models are particularly preferred when the research objective is to examine the evolution of some intertemporal variables such as capital accumulation and economic growth over time (Şenerdem, 2016). Furthermore, given the complexity of fully dynamic models, recursive dynamic CGE models can also be employed as an alternative to static models, in which selected parameters are updated recursively based on the results of previous periods, thereby capturing intertemporal adjustments in the economy (Thurlow, 2008).

The development of a CGE model begins with deciding on an appropriate model design that is consistent with economic theory and the policy scenario being analysed (Böhringer et al., 2003). Once the theoretical framework is established, CGE modelling proceeds through a sequence of standard computational steps, including construction of dataset, specification of functional forms, calibration and policy simulation.

As illustrated in Figure 6.1, the construction of a consistent SAM, which usually serves as the dataset for the CGE model, represents the first and important step in the modelling process.

In CGE models, households are characterized by equations describing their sources of income and demand for goods, whereas firms are represented by equations capturing their production activities and input requirements (Ghaith et al., 2021). Following the SAM construction stage, the model is formulated by defining the behaviour of different economic agents and selecting the functional forms that characterize production technologies and preferences. Typically, the functional form should be continuous, homogeneous of degree zero and consistent with Walras' Law, so as to ensure equilibrium and facilitate the analysis of price variations arising from different economic policies (Annabi et al., 2006). Thus, Constant Elasticity of Substitution (CES) functions and their special cases, such as Cobb-Douglas and Leontief functions, stand out as the most commonly employed functional forms in CGE models, depending on the model's underlying assumptions (Karadag, 1997).

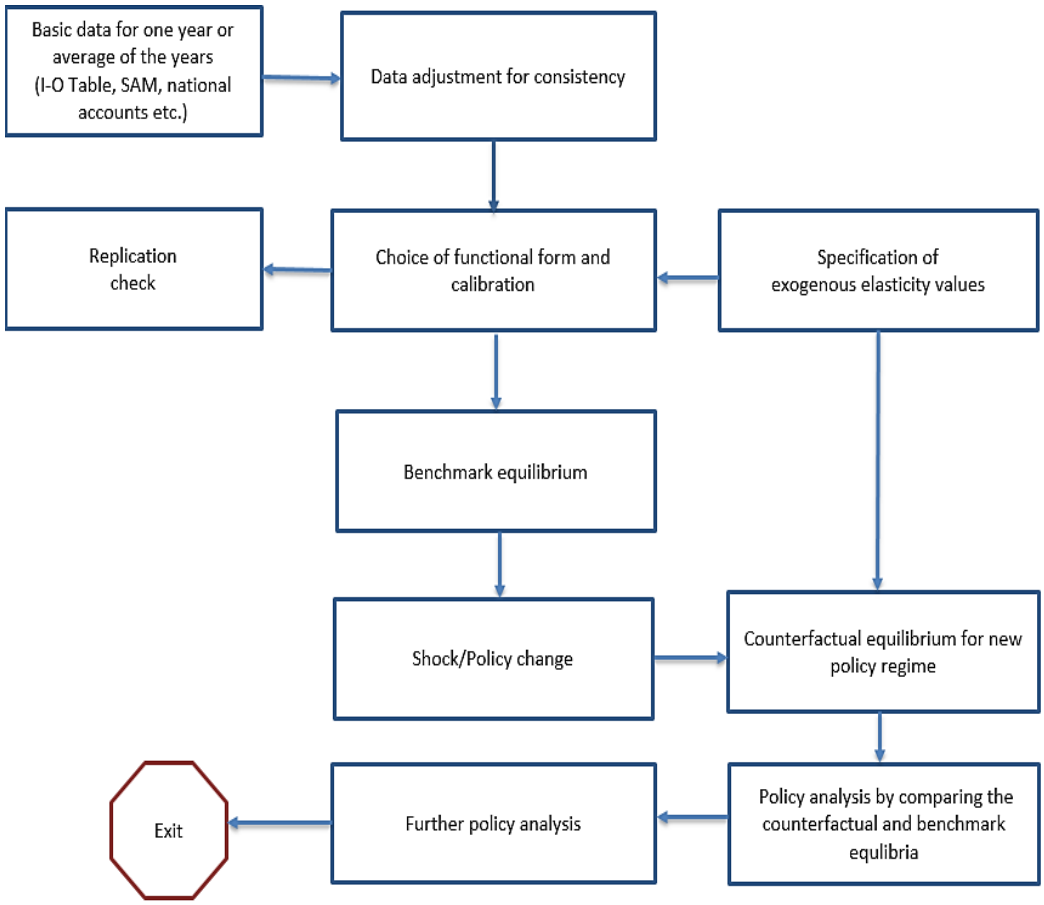


Figure 6.1. Computational steps of a standard CGE model

Source: Adapted from Shoven and Whalley (1984) and Fadali et al. (2012)

In CGE modelling, some functional-form parameters, such as substitution elasticities, are specified exogenously based on the literature, while others such as share parameters are determined through calibration or estimated using econometric methods. The calibration approach assumes that the economy is initially in equilibrium, referred to as the benchmark equilibrium (Sánchez, 2004). Under this assumption, parameters are derived from the benchmark equilibrium so that the model replicates the benchmark data as its initial equilibrium (Roberts, 1994). In this framework, SAM is typically employed for calibration since it also represents an equilibrium of the economy for a given year. However, a key limitation of this calibration approach is that relying solely on observations from a single year exposes it to criticism for having a weak empirical foundation (Döll, 2009). Furthermore, CGE models do not provide empirical validation to assess how well they fit the data or confirm historical facts and the choice of functional forms and many parameters in

the benchmark datasets relies on the modeller's judgment or drawn from secondary sources (Karadag, 1997). At this point, conducting sensitivity analysis can be useful for validating the robustness of results with respect to different parameter values and functional forms. Following successful replication of the benchmark equilibrium and the implementation of sensitivity analysis, the final model is used to perform policy analysis.

In policy simulations, selected parameters or exogenous variables are altered and a new equilibrium is derived as the counterfactual equilibrium. By comparing the counterfactual equilibrium with the benchmark equilibrium, the effects of a policy change on key economic variables, such as consumption, production, employment, income and relative prices, can be revealed by researchers (Böhringer et al., 2003).

In the formulation of CGE models, alongside explicit algebraic representations, the Mathematical Programming System for General Equilibrium (MPSGE), introduced by Rutherford (1994) as a GAMS subsystem, can be applied as a compact non-algebraic alternative. MPSGE is particularly favoured by researchers because it reduces the tedious work of complicated model formulation and allows users to represent all the key features of a CGE model in a tabular format (Pradhan et al., 2023). Indeed, as a high-level programming language for CGE models with complex non-linear structures, MPSGE automatically derives demand and supply functions from input data such as technology, factor endowments, preferences and tax rates (Cretegny et al., 2004). To construct the underlying utility and production functions, it is sufficient to specify reference quantities, reference prices and elasticities (Paltsev, 2004). The MPSGE relies on nested CES structures for utility and production functions, which can be readily incorporated into the model. Thus, it facilitates the construction of operational models and the testing of many alternative specifications (Rutherford, 1999).

As the central focus of this study, the electricity sector requires intricate nested structures to accurately capture substitution possibilities, such as shifts between fossil fuels and renewable energy sources or substitutions between capital and energy inputs. Therefore, this study employs the MPSGE framework to formulate the

GeoCGE-TR model, given its suitability for handling different and complex nesting structures in the electricity sector and its flexibility in analysing multiple scenarios. Furthermore, alongside the development of 2035 scenarios, the study employs a recursive modelling approach.

6.2. Literature on Geothermal Energy in CGE Modelling

Early studies using CGE models mainly focused on the impacts of taxation policies and general welfare analysis. Over time, however, other fields of economics were incorporated into the modelling framework and energy emerged as one of the most prominent research topics in CGE models. This can largely be attributed to the fact that energy is a key input for both production and consumption and is strongly integrated into the economy through significant forward and backward linkages (Dautaj Şenerdem, 2016). Thus, the number of studies on energy-related issues such as climate change, energy transition, energy efficiency, energy subsidies, energy taxation, renewable energy expansion and energy security have rapidly increased in the literature (Ipek & Derin-Gure, 2024). Similarly, the existing literature on Türkiye has largely concentrated on these topics, consistent with the main trends observed in the international literature.

Compared with studies focusing on these specific topics or individual renewable energy sources, the number of studies explicitly addressing geothermal energy has remained limited in the CGE literature (Ipek & Derin-Gure, 2024). Moreover, the literature analysing geothermal-based scenarios has predominantly focused on Indonesia, a country characterized by significant geothermal resource potential, thereby leaving the economic implications of geothermal expansion in other regions relatively understudied. This gap highlights the need for further CGE-based analyses in different national contexts.

Among geothermal-focused CGE studies, Aissa and Hartono (2016) examine the impacts of investing in geothermal electricity generation and substituting fossil fuels with geothermal energy through four scenarios using a static CGE model. The analysis considers four simulation scenarios: (i) a 10% increase in geothermal

electricity production; (ii) a 10% increase in geothermal electricity production combined with a 10% substitution of oil used in power plants with geothermal energy; (iii) a 10% increase in geothermal electricity production together with a 10% substitution of coal with geothermal energy; and (iv) a 10% increase in geothermal electricity production accompanied by a 5% reduction in both oil and coal contributions. The results indicate that the first scenario generates the highest increase in GDP (0.24%) and household income (0.53%), as well as the largest output expansion in the transportation sector, whereas the third scenario leads to the greatest reduction in carbon emissions (5.92%).

To examine pathways for achieving Indonesia's 2030 emission reduction targets, Siagian et al. (2017) develop two scenarios with different power generation mixes and energy demand assumptions. The analysis show that the moderate mitigation scenario involving efficiency measures that reduce total energy demand by 4%, together with a six-fold increase in geothermal power deployment and a fourfold expansion of hydropower, leads to a 15.5% reduction in emissions. The stronger mitigation scenario, which includes a 13% reduction in total energy demand, a sevenfold increase in geothermal deployment, a fivefold expansion of hydropower and the introduction of carbon capture and storage technologies for 4% of fossil-fuelled power plants, results in a 27% reduction in emissions. Furthermore, GDP is projected to increase by 0.6% and 0.3% under these two scenarios, respectively.

Willenbockel et al. (2017) analyse the impacts of increasing the share of geothermal energy in the Kenya's electricity mix from 50% in 2015 to 75% by 2025 using dynamic extension of the standard CGE model. Under this scenario, electricity prices decline by more than 12%, leading to lower supply prices, particularly in sectors such as mining, manufacturing and chemicals. As a result, GDP is projected to be 1.1% and 2.6% higher than in the baseline scenario under low and high fossil fuel price assumptions, respectively. In addition, geothermal expansion reduces refined petrol and crude oil imports by about 10% and alleviates pressure on the balance of payments, leading to valuation of the real exchange rate of 0.7% (under low fuel prices) and 1.2% (under high fuel prices).

Based on a hybrid CGE framework linking top-down macroeconomic modelling with bottom-up technological representation, Hasudungan and Sabaruddin (2018) analyse the economic and environmental effects of feed-in tariffs for renewable energy technologies in Indonesia. The study considers two policy scenarios in which a 15% subsidy is introduced and financed either through an endogenous electricity tax on consumers or through a carbon tax. The findings suggest that both policy options have minimal effects on GDP, sectoral outputs, household welfare and national greenhouse gas emissions. This limited impact is primarily explained by the small contribution of renewable energy sources, particularly geothermal (5%) and hydropower (11%), to Indonesia's electricity generation mix. Among the two policy options, the carbon tax financing mechanism achieves relatively higher emissions reductions but also results in a larger decline in GDP due to higher production costs associated with carbon-intensive fossil fuels.

Using a recursive dynamic CGE model, Hartono et al. (2020b) work on five scenarios examining the removal of electricity and diesel subsidies and the reduction of LPG subsidies, followed by different reallocation schemes of the resulting budget: (i) 100% government savings; (ii) 100% government spending; (iii) 50% government spending and 50% infrastructure investment; (iv) 25% government spending, 50% infrastructure investment and 25% geothermal sector investment; and (v) 50% infrastructure and 50% geothermal sector investment. The results imply that reallocating funds to government spending, infrastructure investment and the geothermal sector generates more positive macroeconomic and environmental outcomes than directing the funds to government savings or general government spending alone. In particular, the fifth scenario prioritizing geothermal investment leads to increases in GDP, real consumption and employment in 2040 by 1.01%, 0.15% and 0.03%, respectively, while sectoral output in the utilities, manufacturing and construction and mining sectors grows by more than 1%. Under the same scenario, emissions and energy intensity are also reduced by 0.80% and 0.95%, respectively.

Wibert et al. (2020) assess the impacts of imposing a carbon tax on either all fossil fuels or only coal and allocating the resulting revenue as a subsidy to geothermal

electricity generation in Indonesia using a hybrid CGE model. The findings indicate that both scenarios reduce national greenhouse gas emissions, ranging from 0.006% to 1.254% depending on the different carbon tax levels. However, the study highlights a trade-off between environmental gains and macroeconomic performance. In the first scenario, taxing all fossil fuels significantly increases geothermal generation by up to 28.9%, thereby reducing emissions; however, it leads to a broader economic contraction due to rising prices of fossil fuels. In contrast, the second policy, which taxes only coal, performs better from a socioeconomic perspective. As coal is mainly used in the industrial sector rather than residential, the government can recycle the tax revenue into geothermal subsidies that help reduce electricity prices. This revenue-recycling mechanism increases geothermal production by about 2.83% at the highest tax level while also improving household welfare and income inequality.

Overall, the existing CGE literature on geothermal energy highlights its potential to promote economic growth, reduce emissions, lower electricity prices and improve energy security. Most geothermal CGE studies utilize policy scenarios involving energy investments, carbon taxes, subsidy reforms and revenue-recycling mechanisms. Furthermore, much of this research is concentrated in specific geographic contexts. Consequently, the broader economy-wide and environmental implications of geothermal energy development remain relatively underexplored in other national settings. In particular, there is limited CGE-based evidence on how geothermal energy expansion interacts with the overall economic structure, sectoral dynamics and environmental outcomes in other countries with significant geothermal potential, such as Türkiye. Thus, the development of a CGE model featuring a detailed electricity-sector structure, including separate representations of geothermal power generation and geothermal heat production, can provide an important foundation for future studies on Türkiye.

Considering that CGE studies on Türkiye rarely model geothermal energy as a distinct electricity generation source and, to the best of our knowledge, none have explicitly examined geothermal-based policy scenarios, this study represents one of the first attempts to both distinguish geothermal energy within a CGE framework and

evaluate its implications through dedicated geothermal scenarios for the country. Furthermore, by introducing geothermal heating alongside geothermal electricity generation, the study extends the existing CGE literature on geothermal energy and enables a more comprehensive representation of geothermal energy within the economy. Beyond addressing these gaps, the findings from the incentive-based scenarios are expected to provide policy-relevant insights into the role of subsidies in supporting geothermal power capacity expansion and achieving Türkiye's long-term geothermal electricity development targets.

6.3. Algebraic Structure of GeoCGE-TR Model

In this section; a static, single-country CGE model calibrated to the balanced SAM in Chapter 5 is introduced. Along with the algebraic formulation, it is intended to provide a transparent and intuitive representation of the core structure of the CGE model (GeoCGE-TR). At this stage, the model is deliberately kept in its simplest form in order to clarify the main equilibrium relationships among production, factor demand, trade, institutions and macroeconomic balances.

In the following section, a more detailed and realistic version of the model in MPSGE format, which is better suited for representing alternative nesting structures, sector-specific production technologies and counterfactual policy scenarios, is presented. This two-step exposition allows the reader first to understand the basic economic logic of the model in explicit algebraic form, before moving to the more flexible MPSGE implementation used for scenario analysis of this study.

6.3.1. Benchmark Data and Accounting Structure

The benchmark equilibrium is obtained directly from the SAM. The model extracts intermediate input use, household consumption, government consumption, investment demand, exports, imports, factor payments, production taxes, household income taxes, institutional transfers and savings from the benchmark accounts. All flows are converted into millions of currency units before calibration.

Let i and j index commodity and production accounts and let f index primary factors. Base-year value added, gross output, composite commodity supply, domestic sales and factor supplies are defined as follows:

$$VA_i^0 = \sum_f FD_{fi}^0 \qquad \forall i \in I \qquad (1)$$

$$X_i^0 = \sum_j \mathrm{INT}_{ji}^0 + \mathrm{VA}_i^0 + \mathrm{TAX_P}_i^0 \qquad \forall i \in I \qquad (2)$$

$$Q_i^0 = \sum_j \mathrm{INT}_{ij}^0 + C_i^0 + \mathrm{CG}_i^0 + \mathrm{INV}_i^0 \qquad \forall i \in I \qquad (3)$$

$$D_i^0 = X_i^0 - E_i^0 \qquad \forall i \in I \qquad (4)$$

$$\mathrm{FS}_f^0 = \sum_i \mathrm{FD}_{fi}^0 \qquad \forall f \in F \qquad (5)$$

where INT_{ij}^0 is the benchmark intermediate use of commodity i by sector j, C_i^0 is household consumption, CG_i^0 is government consumption, INV_i^0 is investment demand, E_i^0 is exports, FD_{fi}^0 is factor demand and $\mathrm{TAX_P}_i^0$ is production tax revenue. The definition of Q_i^0 follows the absorption side of the commodity account, while D_i^0 is obtained as the portion of domestic production that is not exported.

Transfers are denoted by $\mathrm{TR}_{r,s}^0$, where the first subscript identifies the receiving account and the second subscript identifies the paying account. For example, $\mathrm{TR}_{\mathrm{HoH,GOV}}^0$ is the transfer received by households from government, while $\mathrm{TR}_{\mathrm{RoW,GOV}}^0$ is the transfer received by RoW from government. This notation is used consistently in the household, government, external balance and savings-investment equations.

6.3.2. Calibration

The calibration procedure sets the model parameters so that the benchmark SAM is reproduced as an initial equilibrium. Intermediate input coefficients, final demand shares, tax rates, factor shares and trade-function parameters are calibrated from base-year flows.

The fixed input-output coefficient is given by:

$$\text{io}_{ij} = \frac{\text{INT}_{ij}^0}{X_j^0} \qquad \forall i,j \in I \qquad (6)$$

Household, government and investment demand shares are calibrated as:

$$\text{cles}_i = \frac{C_i^0}{\sum_j C_j^0}, \quad \text{cgles}_i = \frac{\text{CG}_i^0}{\sum_j \text{CG}_j^0}, \quad \text{invles}_i = \frac{\text{INV}_i^0}{\sum_j \text{INV}_j^0} \qquad \forall i \in I \qquad (7)$$

Production and household income tax rates are defined as:

$$t_{p,i} = \frac{\text{TAX_P}_i^0}{X_i^0} \qquad \forall i \in I \qquad (8)$$

$$t_y = \frac{\text{TAX_Y}^0}{Y_{\text{HoH}}^0} \qquad (9)$$

Value added is represented by a Cobb-Douglas function. Factor shares and scale parameters are calibrated as:

$$\delta_{fi}^{\text{VA}} = \frac{\text{FD}_{fi}^0}{\text{VA}_i^0} \qquad \forall f \in F,\ i \in I \quad (10)$$

$$\alpha_i^{\text{VA}} = \frac{\text{VA}_i^0}{\prod_f \left(\text{FD}_{fi}^0\right)^{\delta_{fi}^{\text{VA}}}} \qquad \forall i \in I \quad (11)$$

The Armington substitution and the constant elasticity of transformation (CET) parameters are defined as:

$$\rho_i^q = \frac{1}{\sigma_i^q} - 1, \qquad \rho_i^t = \frac{1}{\sigma_i^t} + 1 \qquad \forall i \in I \quad (12)$$

where σ_i^q is the Armington elasticity of substitution and σ_i^t is the elasticity of transformation, both of which are specified exogenously.

The Armington and CET share and scale parameters are then calibrated using benchmark data on imports, domestic sales, exports and output.

6.3.3. Production and Price Block

Each sector produces a single output using a Leontief bundle of intermediate inputs and a Cobb-Douglas value-added composite. Intermediate inputs are used in fixed proportions:

$$\mathrm{INT}_{ij} = \mathrm{io}_{ij} X_j \qquad \forall i, j \in I \quad (13)$$

Value added is produced using labour and capital:

$$\mathrm{VA}_i = \alpha_i^{\mathrm{VA}} \prod_f \mathrm{FD}_{fi}^{\delta_{fi}^{\mathrm{VA}}} \qquad \forall i \in I \quad (14)$$

Cost-minimizing factor demand is given by:

$$\mathrm{FD}_{fi} = \delta_{fi}^{\mathrm{VA}} \frac{\mathrm{PVA}_i \mathrm{VA}_i}{W_f} \qquad \forall f \in F,\ i \in I \quad (15)$$

where PVA_i is the value-added price and W_f is the factor price. Since labour and capital supplies are fixed at their benchmark levels, factor prices adjust endogenously to clear factor markets.

The price block contains three zero-profit or price-linkage equations. The value of domestic production is allocated between domestic sales and exports:

$$P_i X_i = \mathrm{PD}_i D_i + \mathrm{PE}_i E_i \qquad \forall i \in I \quad (16)$$

The value of composite commodity supply is equal to the value of domestic and imported goods:

$$\mathrm{PQ}_i Q_i = \mathrm{PD}_i D_i + \mathrm{PM}_i M_i \qquad \forall i \in I \quad (17)$$

The producer price net of production taxes covers the cost of value added and intermediate inputs:

$$P_i X_i\left(1 - t_{p,i}\right) = \mathrm{PVA}_i \mathrm{VA}_i + \sum_j \mathrm{PQ}_j \, \mathrm{INT}_{ji} \qquad \forall i \in I \quad (18)$$

where $\mathrm{P_i}$ is the producer price, $\mathrm{X_i}$ is total domestic production, $\mathrm{PD_i}$ is the domestic price, $\mathrm{D_i}$ is domestic sales, $\mathrm{PE_i}$ is the export price, $\mathrm{E_i}$ is exports, $\mathrm{PQ_i}$ is the composite commodity price, $\mathrm{Q_i}$ is the composite commodity supply, $\mathrm{PM_i}$ is the import price, $\mathrm{M_i}$ is imports, $\mathrm{t_{p,i}}$ is the production tax rate and $\mathrm{INT_{ji}}$ is the intermediate input demand for commodity i by sector j.

6.3.4. Domestic and Foreign Trade

The model distinguishes between imported and domestically produced varieties based on the Armington (1969) assumption that these goods are imperfect substitutes. Composite supply is defined as a constant elasticity of substitution aggregation of imports and domestic sales:

$$Q_i = \alpha_i^q \left[\delta_i^q M_i^{-\rho_i^q} + \left(1 - \delta_i^q\right) D_i^{-\rho_i^q}\right]^{-1/\rho_i^q} \qquad \forall i \in I \qquad (19)$$

The associated import-demand function is:

$$M_i = D_i \left[\left(\frac{\mathrm{PD}_i}{\mathrm{PM}_i}\right)\left(\frac{\delta_i^q}{1 - \delta_i^q}\right)\right]^{1/\left(1+\rho_i^q\right)} \qquad \forall i \in I \quad (20)$$

On the supply side, producers allocate output between exports and domestic sales through a CET function:

$$X_i = \alpha_i^t \left[\gamma_i^t E_i^{\rho_i^t} + (1 - \gamma_i^t) D_i^{\rho_i^t}\right]^{1/\rho_i^t} \qquad \forall i \in I \quad (21)$$

The export supply function is:

$$E_i = D_i \left[\left(\frac{\mathrm{PE}_i}{\mathrm{PD}_i} \right) \left(\frac{1 - \gamma_i^t}{\gamma_i^t} \right) \right]^{1/(\rho_i^t - 1)} \qquad \forall i \in I \quad (22)$$

where α_i^q and α_i^t denote the scale parameters, while δ_i^q and γ_i^t are the share parameters of the Armington aggregation function and the CET transformation function, respectively.

Together, the Armington and CET blocks allow domestic and foreign goods to be imperfect substitutes in demand and domestic and export markets to be imperfectly transformable in supply.

6.3.5. Institutions, Taxes, Transfers and Final Demand

The model assumes a single representative household that maximizes utility. Household receives income from factor ownership, transfers from government, transfers from the RoW and transfers from the capital account. Household income is defined as:

$$Y_{\mathrm{HoH}} = \sum_f W_f \, \mathrm{FS}_f^0 + \mathrm{TR}_{\mathrm{HoH,GOV}}^0 + \mathrm{EXR} \cdot \mathrm{TR}_{\mathrm{HoH,RoW}}^0 + \mathrm{TR}_{\mathrm{HoH,CACC}}^0 \quad (23)$$

Household consumption demand is allocated across commodities using fixed budget shares after deducting household income taxes and savings:

$$\mathrm{PQ}_i C_i = \mathrm{cles}_i \left[Y_{\mathrm{HoH}} (1 - t_y) - \mathrm{SAV}_{\mathrm{HoH}} \right] \qquad \forall i \in I \quad (24)$$

Government income consists of production tax revenue, household income tax revenue, transfers from the RoW and an additional residual government income component calibrated from the SAM:

$$Y_{\mathrm{GOV}} = \sum_i t_{p,i}\, P_i X_i + t_y Y_{\mathrm{HoH}} + \mathrm{EXR} \cdot \mathrm{TR}^0_{\mathrm{GOV,RoW}} + \mathrm{GOV_OTHER}^0 \quad (25)$$

Government consumption is allocated across commodities according to fixed expenditure shares after government savings and transfer payments are deducted:

$$\mathrm{PQ}_i \mathrm{CG}_i = \mathrm{cgles}_i \left[Y_{\mathrm{GOV}} - \mathrm{SAV}_{\mathrm{GOV}} - \mathrm{TR}^0_{\mathrm{HoH,GOV}} - \mathrm{EXR} \cdot \mathrm{TR}^0_{\mathrm{RoW,GOV}} \right] \quad \forall i \in I \quad (26)$$

Investment demand is represented by a fixed-share investment basket:

$$\mathrm{PQ}_i \mathrm{INV}_i = \mathrm{invles}_i \sum_j \mathrm{PQ}_j\, \mathrm{INV}_j \quad \forall i \in I \quad (27)$$

This formulation fixes the commodity composition of investment while allowing the aggregate level of investment to be determined by the savings-investment balance.

6.3.6. Market-clearing Conditions and Macroeconomic Closure

Commodity markets clear when composite supply equals intermediate demand, household consumption, government consumption and investment demand:

$$Q_i = \sum_j \mathrm{INT}_{ij} + C_i + \mathrm{CG}_i + \mathrm{INV}_i \quad \forall i \in I \quad (28)$$

Factor markets clear when total sectoral demand for each factor equals its fixed benchmark supply:

$$\sum_i \mathrm{FD}_{fi} = \mathrm{FS}^0_f \quad \forall f \in F \quad (29)$$

The external account is specified without an explicit foreign savings variable. With the exchange rate fixed at unity, the balance-of-payments condition equates imports

and government transfers to the rest of the world with exports and transfers from the rest of the world to domestic institutions:

$$\sum_i \mathrm{PM}_i\, M_i + \mathrm{EXR} \cdot \mathrm{TR}^0_{\mathrm{RoW,GOV}} = \sum_i \mathrm{PE}_i\, E_i + \mathrm{EXR} \cdot \mathrm{TR}^0_{\mathrm{GOV,RoW}} + \mathrm{EXR} \cdot \mathrm{TR}^0_{\mathrm{HoH,RoW}} \tag{30}$$

The savings-investment balance is:

$$\sum_i \mathrm{PQ}_i\, \mathrm{INV}_i + \mathrm{TR}^0_{\mathrm{HoH,CACC}} = \mathrm{SAV}_{\mathrm{HoH}} + \mathrm{SAV}_{\mathrm{GOV}} \tag{31}$$

The term $\mathrm{TR}^0_{\mathrm{HoH,CACC}}$ represents the transfer from the capital account to households and is therefore deducted from the resources available for physical investment demand. Household and government savings are fixed at benchmark-consistent levels:

$$\mathrm{SAV}_{\mathrm{HoH}} = Y^0_{\mathrm{HoH}}(1 - t_y) - \sum_i C^0_i \tag{32}$$

$$\mathrm{SAV}_{\mathrm{GOV}} = Y^0_{\mathrm{GOV}} - \sum_i \mathrm{CG}^0_i - \mathrm{TR}^0_{\mathrm{HoH,GOV}} - \mathrm{TR}^0_{\mathrm{RoW,GOV}} \tag{33}$$

Accordingly, aggregate investment adjusts to the level of available domestic savings after accounting for the capital-account transfer to households. The absence of an explicit foreign savings variable implies that the external account is closed directly through the balance-of-payments equation rather than through an exogenous current-account deficit or surplus.

6.4. Formulation of GeoMPSGE-TR Model

CGE modelling relies on well-specified utility and production functions to capture the substitution possibilities available to households and firms in the economy; however, specifying functional forms that are both theoretically consistent and

practically manageable remains a significant challenge, particularly given the complexity of real-world economic structures (Lechner, 2011). In this context, nesting, a commonly employed approach in CGE models, allows for the representation of substitution patterns across multiple hierarchical levels.

As outlined in the algebraic formulation of the CGE model, production function is represented by a two-stage structure: at the lower level, capital and labour combine to form value-added through a Cobb-Douglas function, while intermediate inputs are used in fixed proportions following a Leontief specification; at the upper level, total output is produced as a fixed-proportion combination of value-added and intermediate inputs. However, the electricity sector, which constitutes the main focus of this study, requires special attention in defining the nesting structures. Indeed, electricity, as a composite commodity produced from different energy technologies, involves distinct input structures and substitution possibilities. To illustrate, electricity from dispatchable generation technologies (hydro, geothermal, biomass and fossil fuels) can be modelled as perfect substitutes, whereas electricity from intermittent sources such as wind and solar is treated as an imperfect but close substitute for these technologies. To accommodate these diverse substitution possibilities in the electricity sector-focused CGE model, hereafter referred to as the GeoMPSGE-TR model, this study adopts a detailed nesting structure for the electricity sector and for individual generation technologies. In this way, the model incorporates a macroeconomic representation of non-electric sectors alongside a detailed specification of the electricity sector.

In this study, the algebraic GeoCGE-TR model presented in Section 6.3 is initially developed in GAMS and checked for calibration in order to verify the consistency of the benchmark equilibrium and the underlying theoretical structure. However, due to the limitations associated with representing the electricity sector within the algebraic framework, the analysis proceeds using the MPSGE-equivalent version of the model. Accordingly, the model is reformulated within the MPSGE framework to provide a more flexible and internally consistent structure for capturing the multi-layered production structures and substitution relationships within the electricity sector.

A key advantage of the MPSGE modelling language is its ability to represent highly disaggregated sectoral structures and complex nested production and consumption technologies in a compact and transparent way. In applied CGE modelling, sectoral disaggregation is particularly important when policy shocks affect activities asymmetrically, as in the case of energy, environmental, trade, or tax policies. MPSGE facilitates this by allowing each production activity, commodity and factor market to be defined explicitly while preserving the underlying general equilibrium consistency. In addition, the language is especially well suited for representing multi-level nesting structures, such as the separation of intermediate inputs, value added, energy aggregates, electricity technologies and substitution possibilities among fuels or factors. In this way, MPSGE allows assessing the economy-wide feedback loops triggered by target-share mandates, technology subsidies and factor resource reallocations across the wider economy.

6.4.1. Structural Classifications: Sets, Sectors and Institutional Agents

The sets in the MPSGE model are defined based on the structure of the disaggregated SAM and the model is built upon the balanced SAM presented in Section 5.9. They capture production, income and consumption flows across 23 core sectors, together with detailed disaggregation of the electricity and steam sectors, two primary factors of production (labor and capital) and two principal institutions (households and government), as presented in Table 6.1.

Table 6.1. Sets used in the MPSGE model

```
SETS
    acc          All SAM Accounts /

                 AGRF        agriculture&forestry&fishing
                 MIN         mining&quarrying
                 FODPR       food processing
                 TEXCLOT     textile&clothing
                 RPETR       refined petroleum
                 CHE         chemicals
                 MACHEQ      machinery&equipment
                 ELECTRO     electronics
                 OTHMAN      other manufacturing
                 EBIO        electricity-biomass
                 EHYD        electricity-hydro
                 EGEO        electricity-geothermal
                 ESOL        electricity-solar
```

Table 6.1. (continued)

```
EWND        electricity-wind
EOTH        electricity-other
SGEO        steam-geothermal
SOTH        steam-other
NGAS        natural gas
CONSMAT     construction&material
HOTRES      hotels&restaurants
TRANSCOM    transportation&communication
FIRE        finance&insurance&real estate
OTH         others
LAB         labor
CAP         capital
HoH         households
GOV         government
CACC        capital accumulation
RoW         rest of the world/
```

To precisely capture energy-economy feedback mechanisms, the sets are further classified into distinct subsets according to their technological and functional characteristics as given in Table 6.2. A key feature of the model is the detailed disaggregation of the power sector into specific electricity generation technologies, including a further distinction between intermittent and non-intermittent renewable energy sources. The model also represents geothermal electricity and geothermal heat generation (geothermal steam) as separate activities, enabling a more comprehensive assessment of the technological and economic role of geothermal energy within the production and energy system.

Table 6.2. Subsets used in the MPSGE model

```
SETS
    i(acc)        Sectors and commodities
                  /AGRF, MIN, FODPR, TEXCLOT, RPETR, CHE, MACHEQ, ELECTRO, OTHMAN,
                  EBIO, EHYD, EGEO, ESOL, EWND, EOTH, SGEO, SOTH, NGAS,
                  CONSMAT, HOTRES, TRANSCOM, FIRE, OTH/

    f(acc)        Factors of production
                  /LAB, CAP/

    CAP(f)        Capital /CAP/

    LAB(f)        Labor   /LAB/

    agri(i)       Agriculture sector /AGRF/

    ene(i)        Energy related sectors excluding power
                  /MIN, RPETR, NGAS, SGEO, SOTH/
```

Table 6.2. (continued)

```
    eneNonStm(i) Energy related sectors excluding power and steam
                 /MIN, RPETR, NGAS/

    nene(i)      Non-energy sectors
                 /AGRF, FODPR, TEXCLOT, CHE, MACHEQ, ELECTRO, OTHMAN,
                 CONSMAT, HOTRES, TRANSCOM, FIRE, OTH/

    nele(i)      Non-electricity sectors
                 /AGRF, MIN, FODPR, TEXCLOT, RPETR, CHE, MACHEQ, ELECTRO, OTHMAN,
                 SGEO, SOTH, NGAS, CONSMAT, HOTRES, TRANSCOM, FIRE, OTH/

    nelenagri(i) Non-electricity sectors excluding agriculture
                 /MIN, FODPR, TEXCLOT, RPETR, CHE, MACHEQ, ELECTRO, OTHMAN,
                 SGEO, SOTH, NGAS, CONSMAT, HOTRES, TRANSCOM, FIRE, OTH/

    nelengeo(i) Non-electricity sectors excluding geothermal steam
                 /AGRF, MIN, FODPR, TEXCLOT, RPETR, CHE, MACHEQ, ELECTRO, OTHMAN,
                 SOTH, NGAS, CONSMAT, HOTRES, TRANSCOM, FIRE, OTH/

    nelenstm(i) Non-electricity sectors excluding steam
                 /AGRF, MIN, FODPR, TEXCLOT, RPETR, CHE, MACHEQ, ELECTRO, OTHMAN,
                 NGAS, CONSMAT, HOTRES, TRANSCOM, FIRE, OTH/

    ele(i)       Electricity generation sectors
                 /EBIO, EHYD, EGEO, ESOL, EWND, EOTH/

    stm(i)       Steam sectors
                 /SGEO, SOTH/

    eleGeo(i)    Geothermal electricity /EGEO/

    allGeo(i)    Geothermal electricity and steam
                 /EGEO, SGEO/

    eleBH(i)     Electricity generation sectors - bio and hydro
                 /EBIO, EHYD /

    eNonGeo(i)   Electricity generation sectors excluding geothermal
                 /EBIO, EHYD, ESOL, EWND, EOTH /

    eleBHO(i)    Electricity generation sectors - bio hydro and other
                 /EBIO, EHYD, EOTH /

    eleRnw(i)    Electricity generation sectors - renewables
                 /EBIO, EHYD, EGEO, ESOL, EWND /

    eleOth(i)    Other electricity /EOTH /

   eleRnwSoWn(i) Electricity generation sectors – intermittent renewables
                  /ESOL, EWND /

eleRnwNonSoWn(i) Electricity generation sectors – non-intermittent renewables
                     /EBIO, EHYD, EGEO/;
```

Table 6.3 presents the main structural blocks of the MPSGE model, namely sectors, commodities and consumers. The "sectors" block defines the production activities of the economy, where each sector corresponds to an activity level representing a specific production process, including Armington (CES), CET and Leontief specifications. The "commodities" block specifies the set of commodities and associated price variables in the model. Meanwhile, the "consumers" block defines the economic agents and institutions within the economy, such as households and government, which receive income and allocate expenditures according to the model structure.

Table 6. 3. Sectors, commodities and consumers in the MPSGE model formulation

```
$model:GeoMPSGE-TR

$sectors:
    y(i)                ! Supply | all sectors
    yy(i)$nelengeo(i)   ! Supply | domestic-export allocation - all sectors
                        ! excluding electricity and geothermal steam
    yy_ele              ! Supply | domestic-export allocation - electricity
    yy_geo              ! Supply | domestic-export allocation - geothermal
    ya(i)$nele(i)       ! Armington composite | all sectors excluding
                        ! electricity
    ya_ele              ! Armington composite | electricity
    eleAgg              ! Electricity composite | conventional and
                        ! intermittent
    yCon                ! Private consumption
    yGov                ! Government consumption
    yInv                ! Investment accumulation
    yUtil               ! Consumer utility
    yNuc$nucFlag        ! Backstop nuclear

$commodities:
    p(i)$nele(i)        ! Output price
    pd(i)$nele(i)       ! Output price – domestic
    pa(i)$nele(i)       ! Armington price | non-electricity
    pa_ele              ! Armington price | electricity
    pd_ele              ! Composite electricity price - domestic
    pele                ! Electricity price
    peleSW              ! Electricity price | intermittent resources-solar
                        ! and wind
    peleBHO             ! Electricity price | bio, hydro and other
    peleGEO             ! Electricity price | geothermal
    pf(f)               ! Primary factors rent
    ptsf(eleRnw)        ! Price of technology specific factor for
                        ! renewables
    pxm                 ! Price of the foreign trade composite
    pnum                ! Numeriare
    pCon                ! Price index of private consumption
    pGov                ! Price index of government consumption
    pInv                ! Price index of investment
    pU                  ! Price index of consumer utility
    ptsfNuc$nucFlag     ! Technology specific factor rent | backstop
                        ! nuclear

$consumers:
    hh                  ! Households
    gov                 ! Government
```

6.4.2. Production Technology

In the MPSGE framework, the production block generating a cost function represents the supply side of the economy (Markusen, 2002). The first line of the block defines the production activity together with the associated substitution and transformation elasticities. Within the block, the first column specifies commodity outputs ("O:") and inputs ("I:"), while the second column (starting with "Q:") reports the corresponding benchmark commodity quantities. Next to the benchmark quantities, user defined tags (e.g., "m", "st", "kl" etc. as employed in the following tables) can be used to define the nesting structure. In case of taxes, "A: z T: tx" notation assigns the tax revenue to agent "z" with a tax rate of "tx".

In the MPSGE model, the supply side of the economy features multi-tiered CES nesting trees. These nested structures govern how producers substitute inputs when relative prices shift. The production technologies differ across the sectors and thus need to be represented in the model (Kat et al., 2018). Within this framework, production is designed around two main nesting hierarchy schemes for agricultural activities and non-agricultural activities as well as several schemes for the power sector technologies. These nesting structures mainly follow the approach of Kat et al. (2018), which builds upon earlier versions of the MIT EPPA model (Paltsev et al., 2005; Chen et al., 2015) and the MIT USREP model (Rausch et al., 2009; Lanz & Rausch, 2011).

Table 6.4. Supply block for agriculture sector

```
$prod:y(i)$(agri(i))    s:1     kl:1  eem:1   m(eem):1  ee(eem):1  e(ee):1
st(e):2

    O:p(i)                                      Q:X0(i)        A:GOV T:t_p(i)

    I:pa(j)$(nene(j) AND INT0(j,i))             Q:INT0(j,i)    m:
    I:pa(j)$(eneNonStm(j) AND INT0(j,i))        Q:INT0(j,i)    e:
    I:pa(j)$(stm(j) AND INT0(j,i))              Q:INT0(j,i)    st:
    I:pa_ele$ELEINT0(i)                         Q:ELEINT0(i)   ee:
    I:pf(f)$(FD0(f,i))                          Q:FD0(f,i)     kl:
```

The supply of agricultural activities formulated in Table 6.4 represents a multi-level nesting hierarchy as illustrated in Figure 6.2. At the top-level nest, the production

system exhibits a unitary elasticity of substitution, i.e. s:1 (Cobb-Douglas (C-D) structure), balancing the primary factor nest of capital and labor against an intermediate material-energy composite under a C-D relation, i.e., eem:1, which branches into non-energy intermediate material flows (m) and an energy-electricity complex (ee) under unit elasticity. Within the intermediate material line (m:1), standard non-energy intermediate inputs (nene) are absorbed into production. Crucially, the energy branch is controlled by a multi-layered structure designed to capture realistic fuel-switching and electrification options:

- The Extended Energy Nest (ee:1): At this stage, the production tree aggregates the unified macroeconomic electricity commodity (pa_ele) with a lower-level energy aggregate (e), regulating how industries balance power grid consumption against thermal energy alternatives.
- The Baseline Energy Nest (e:1): This node handles the trade-off between primary non-electricity fossil fuels (eneNonStm, such as coal, oil, or natural gas) and localized steam delivery networks (st).
- The Thermal Steam Sub-Nest (st:2): At the deepest layer of the hierarchy, a dedicated steam nest features an elevated elasticity of substitution, i.e., st:2. This high substitution elasticity regulates how fluidly industrial processes can substitute other steam and the steam from geothermal.

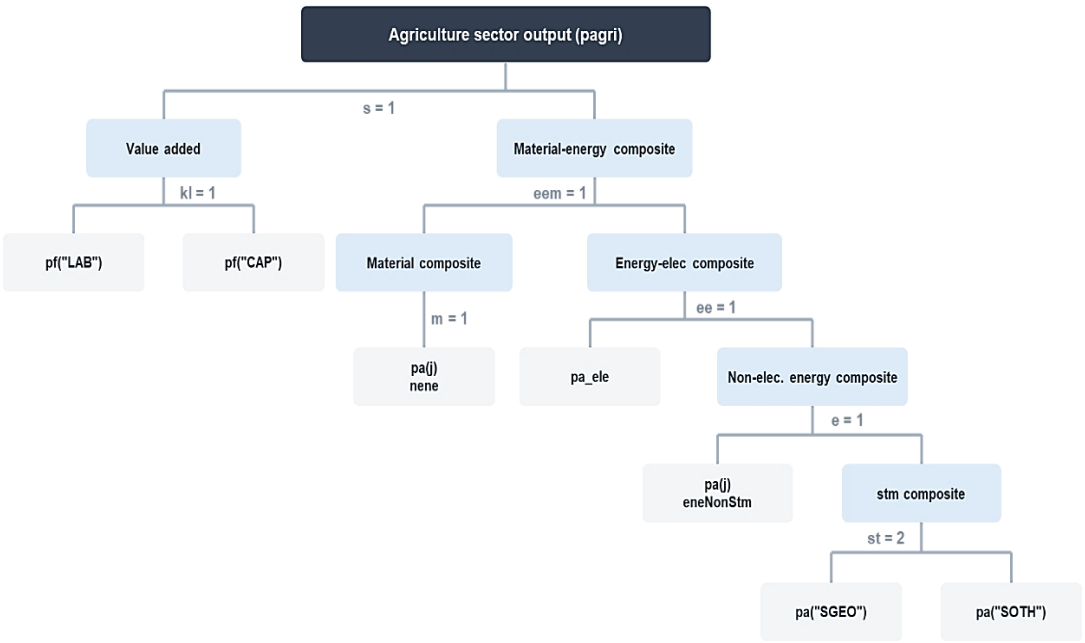


Figure 6.2. Nesting structure for agriculture sector

Finally, ad-valorem production taxes (t_p) apply directly to the final gross sectoral output endogenously channelled as a revenue stream to the government account, i.e., a:gov and t:t_p(i). It is worth noting that, in the model specification, the activity and commodity accounts of the SAM are consolidated into a single account, while commodity taxes in the SAM are treated as production taxes. This simplification is adopted to reduce model complexity and is considered appropriate given the assumed one-to-one correspondence between activities and commodities, whereby each activity is assumed to produce a unique commodity and each commodity is supplied by a single activity.

Table 6.5. Supply block for non-electric sectors excluding agriculture

$prod:y(i)$(nelenagri(i)) *s:1 eekl:1 kl(eekl):1 ee(eekl):1 e(ee):1 st(e):2*		
O:p(i)	*Q:X0(i)*	*A:GOV T:t_p(i)*
I:pa(j)$(nene(j) AND INT0(j,i))	*Q:INT0(j,i)*	
I:pa(j)$(eneNonStm(j) AND INT0(j,i))	*Q:INT0(j,i)*	*e:*
I:pa(j)$(stm(j) AND INT0(j,i))	*Q:INT0(j,i)*	*st:*
I:pa_ele$ELEINT0(i)	*Q:ELEINT0(i)*	*ee:*
I:pf(f)$(FD0(f,i))	*Q:FD0(f,i)*	*kl:*

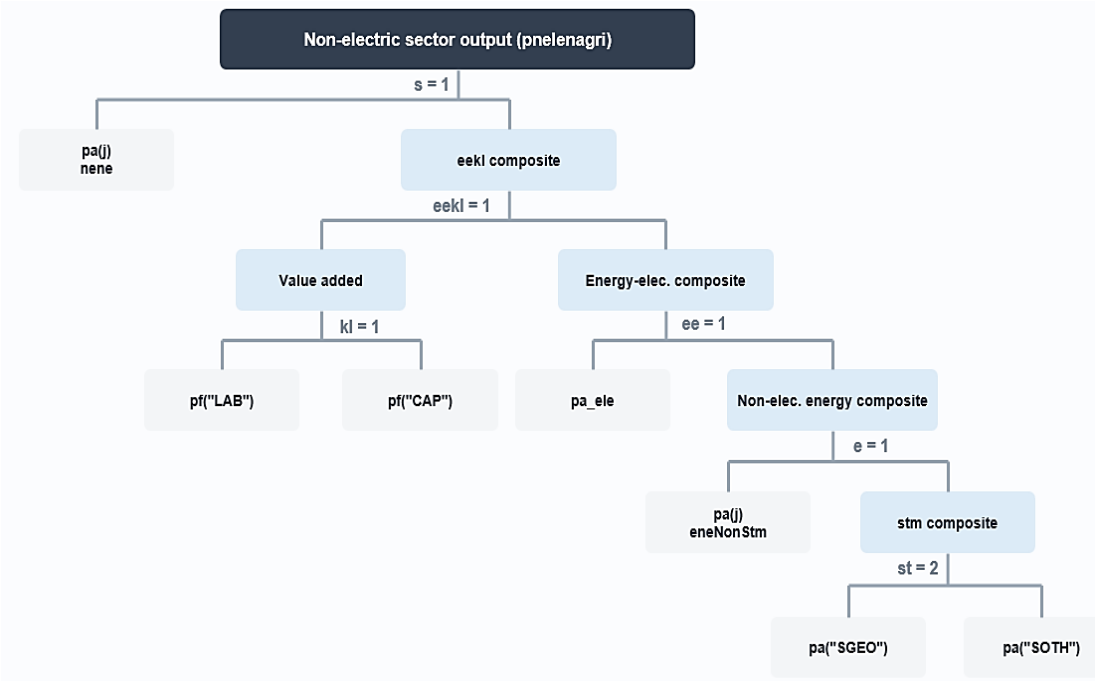


Figure 6.3. Nesting structure for non-electric sectors excluding agriculture

The supply block and nesting structure for non-electric sectors, excluding agriculture, is presented in Table 6.5 and illustrated in Figure 6.3. Unlike the agricultural sector, the top-level production nest combines the eekl composite with non-energy inputs, rather than value added, through a C-D aggregation function. On the other hand, at the first sub-tier, value added is combined with the energy-electricity composite. The remaining lower-level nests, starting from the energy-electricity composite, follow the same nesting structure as that specified for the agricultural sector.

Unlike conventional industrial sectors, the power sector is highly disaggregated into distinct technological segments to accurately reflect fuel dependencies, grid constraints and resource availability. Within this framework, electricity generation is represented by three operational categories, intermittent technologies such as wind and solar, other renewable technologies and conventional generation technologies such as coal and natural gas, each characterized by its own customized nested production hierarchy.

Table 6.6. Supply block for wind and solar

```
$prod:y(i)$eleRnwSoWn(i)   s:0.3   klm:1   st(klm):2

    O:peleSW                                        Q:X0(i)        A:GOV T:t_p(i)

    I:pa(j)$(nelenstm(j) AND INT0(j,i))             Q:INT0(j,i)     klm:
    I:pa(j)$(stm(j) AND INT0(j,i))                  Q:INT0(j,i)     st:
    I:pa_ele$ELEINT0(i)                             Q:ELEINT0(i)    klm:
    I:pf(f)$(FD0(f,i))                              Q:FD0_(f,i)     klm:
    I:ptsf(i)                                       Q:TFD0_(i)
```

Table 6.6 and Figure 6.4 present the supply blocks and nesting structures for wind and solar. At the top-level production tier, a low elasticity of substitution, s: 0.3, regulates the transformation boundary between the endogenously determined sector-specific fixed natural resource (ptsf) (Kat et al., 2018) and the rest of the input factor composite (klm) which are aggregated under C-D relation whereas steam is represented in a manner consistent with the other supply blocks.

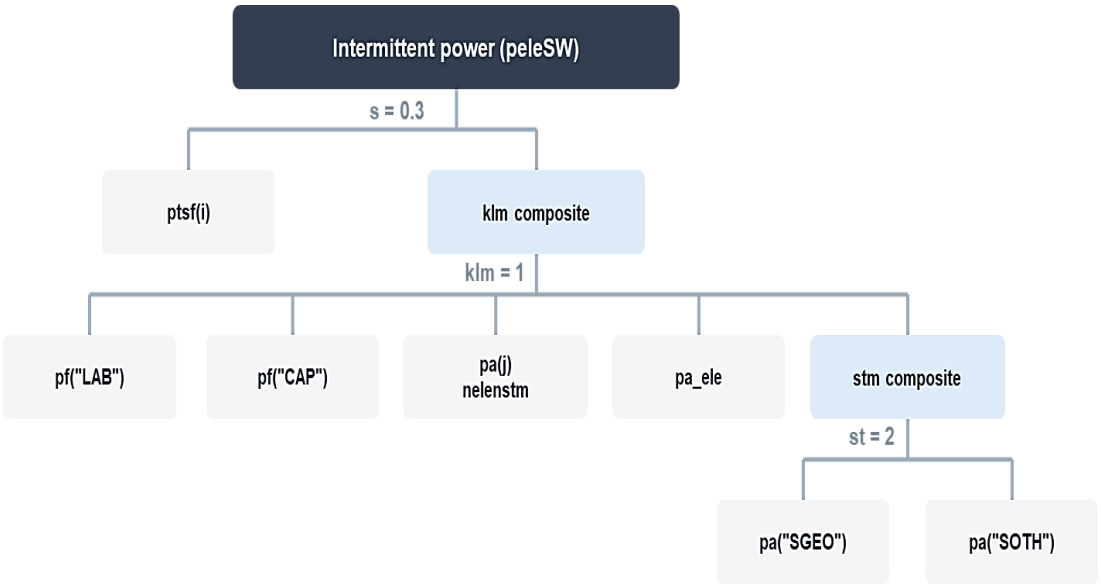


Figure 6.4. Nesting structure for wind and solar

Table 6.7 and Figure 6.5 present the supply block and nesting structure for dispatchable renewable technologies such as biomass, hydro and geothermal. The production structure for these renewables employs a four-tier nesting framework to capture their physical and operational rigidities. At the top level, non-electric sector (excluding steam) inputs, electricity, klt and steam composite are combined in fixed Leontief proportions. At the first sub-tier, the capital-labour composite is combined with the fixed natural resource endowment, with a substitution elasticity of 0.3 (klt: 0.3), reflecting the limited substitutability between value added and resource availability. The steam composite is structured in the same manner as in the other energy technologies.

Table 6.7. Supply block for biomass, hydro and geothermal

```
$prod:y(i)$eleBH(i) (eleGeo for geothermal)   s:0  klt:0.3  kl(klt):1  st:2

    O:peleBHO                                    Q:X0(i)        A:GOV T:t_p(i)

    I:pa(j)$(nelenstm(j) AND INT0(j,i))          Q:INT0(j,i)
    I:pa(j)$(stm(j) AND INT0(j,i))               Q:INT0(j,i)     st:
    I:pa_ele$ELEINT0(i)                          Q:ELEINT0(i)
    I:pf(f)$(FD0(f,i))                           Q:FD0_(f,i)     kl:
    I:ptsf(i)                                    Q:TFD0_(i)      klt:
```

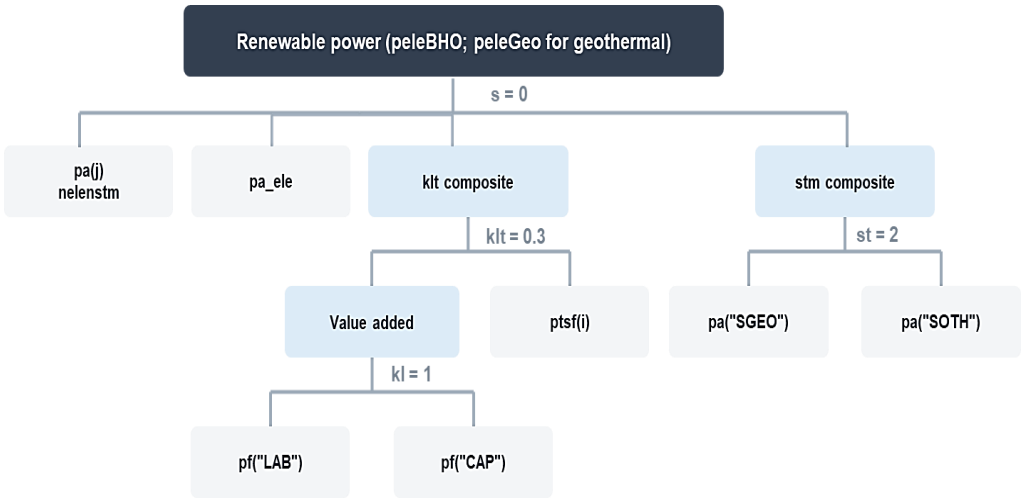


Figure 6.5. Nesting structure for biomass, hydro and geothermal

The eleOth production block in Table 6.8 abstracts from fixed resource constraints to model standard power generation via a five-tier CES hierarchy. As seen in Figure 6.6 strict Leontief top-level, i.e., s:0, aggregates non-energy inputs to kle composite. This balances a standard C-D value-added nest against a Leontief energy nest that locks the physical proportions of fossil fuels and grid electricity.

Table 6.8. Supply block for other technologies: coal and natural gas

$prod:y(i)$eleOth(i)	*s:0*	*kle:0.1*	*kl(kle):1*	*ee(kle):0*	*st(ee):2*
O:peleBHO			*Q:X0(i)*	*A:GOV T:t_p(i)*	
I:pa(j)$(nene(j) AND INT0(j,i))			*Q:INT0(j,i)*		
I:pa(j)$(eneNonStm(j) AND INT0(j,i))			*Q:INT0(j,i)*	*ee:*	
I:pa(j)$(stm(j) AND INT0(j,i))			*Q:INT0(j,i)*	*st:*	
I:pa_ele$ELEINT0(i)			*Q:ELEINT0(i)*	*ee:*	
I:PF(f)$(FD0(f,i))			*Q:FD0(f,i)*	*kl:*	

As a backstop technology, nuclear energy is also incorporated into the GeoMPSGE-TR model. Although nuclear power plants are not yet operational in Türkiye, they may play a significant role in shaping the country's future electricity generation mix. Thus, the supply block and nesting structure for nuclear energy are presented in Table 6.9 and Figure 6.7, respectively. Although the nesting structure closely resembles that of dispatchable renewable technologies, the nuclear supply block is specified benchmark input and output coefficients in the same manner with Kat et al. (2018), reflecting the absence of operational nuclear power generation in Türkiye.

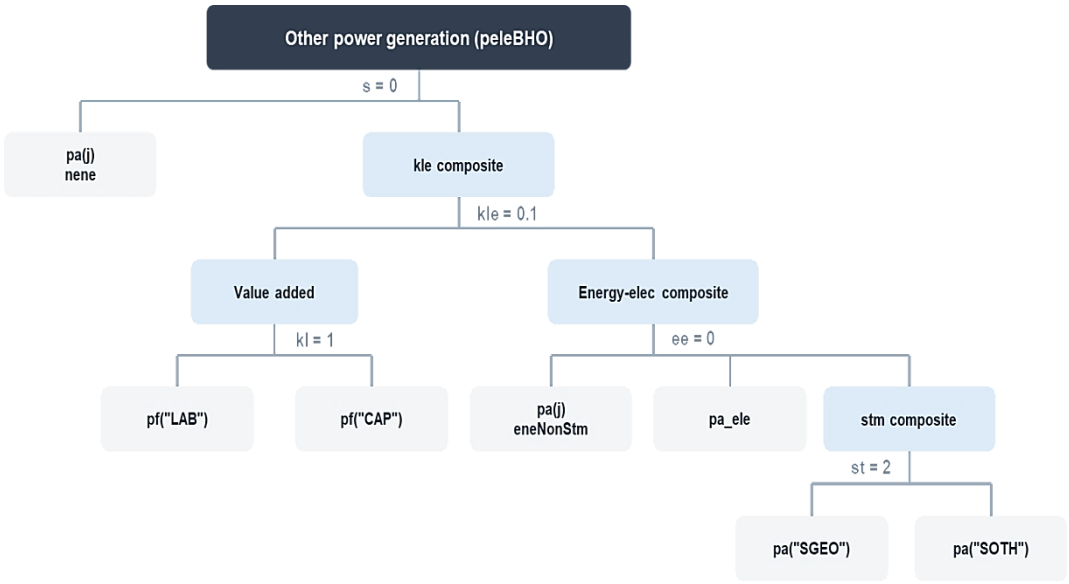


Figure 6.6. Nesting structure for other technologies: coal and natural gas

Table 6.9. Supply block for nuclear

```
$prod:yNuc$nucFlag      s:0     klt:0.3      kl(klt):1        st:2

    O:peleBHO                                 Q:(1.00)        A:GOV T:t_pNuc

    I:pa(j)$(nelenstm(j))                     Q:(intNUC0(j))
    I:pa(j)$(stm(j))                          Q:(0.000)        st:
    I:pa_ele                                  Q:(0.055)
    I:pf("LAB")                               Q:(0.222)       kl:
    I:pf("CAP")                               Q:(0.361)       kl:
    I:ptsfNuc                                 Q:(tsfNuc0)     klt:
```

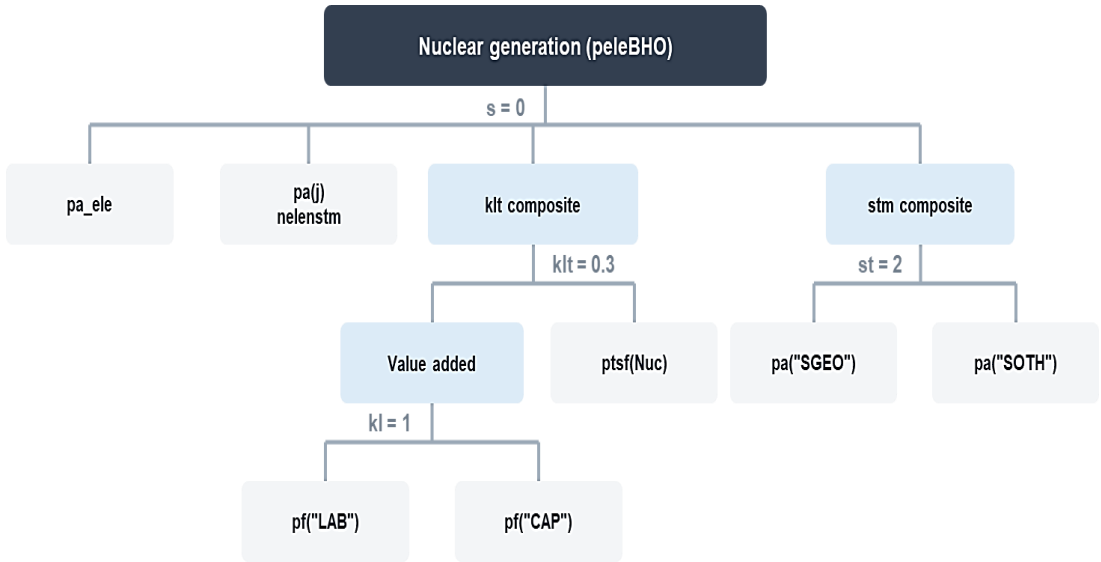


Figure 6.7. Nesting structure for nuclear

6.4.3. Supply and Transformation

The allocation of gross output across different markets is governed by a CET function. The three blocks provided in Table 6.10, Table 6.11 and Table 6.12 define the CET frontier, which allocates domestic production between domestic sales and exports. Non-electric commodities and aggregate electricity utilize a straightforward single-tier CET mechanism as seen in Figure 6.8. In contrast, the geothermal sector employs a sophisticated joint-production structure as in Figure 6.9: it bundles geothermal electricity and steam outputs into a unified supply composite, which is then simultaneously transformed into distinct domestic and export market streams through product-specific sub-nests.

Table 6.10. Supply block for non-electric commodities with CET

```
$prod:yy(i)$nelengeo(i)  t:2

    I:p(i)                                      Q:X0(i)

    O:pd(i)                                     Q:D0(i)
    O:pxm$E0(i)                                 Q:E0(i)
```

Table 6.11. Supply block for electricity excluding geothermal with CET

```
$prod:yy_ele    t:2

  I:pele                    Q:(sum(eNonGeo,D0(eNonGeo))+sum(eNonGeo,E0(eNonGeo)))

  O:pd_ele                  Q:(sum(eNonGeo,D0(eNonGeo)))
  O:pxm                     Q:(sum(eNonGeo,E0(eNonGeo)))
```

Table 6.12. Supply block for geothermal with CET

```
$prod:yy_geo    t:1  el(t):2    st(t):2    i:0

    I:pele                          Q:(D0("EGEO")+E0("EGEO"))       i:
    I:p("SGEO")                     Q:(D0("SGEO")+E0("SGEO"))       i:

    O:pd_ele                        Q:(D0("EGEO"))  el:
    O:pd("SGEO")                    Q:(D0("SGEO"))  st:
    O:pxm                           Q:(E0("EGEO"))  el:
    O:pxm                           Q:(E0("SGEO"))  st:
```

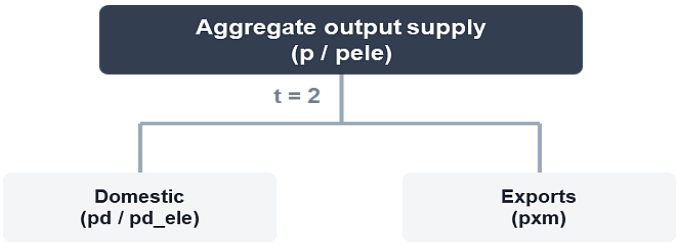


Figure 6.8. CET Nesting structure: domestic vs. exports

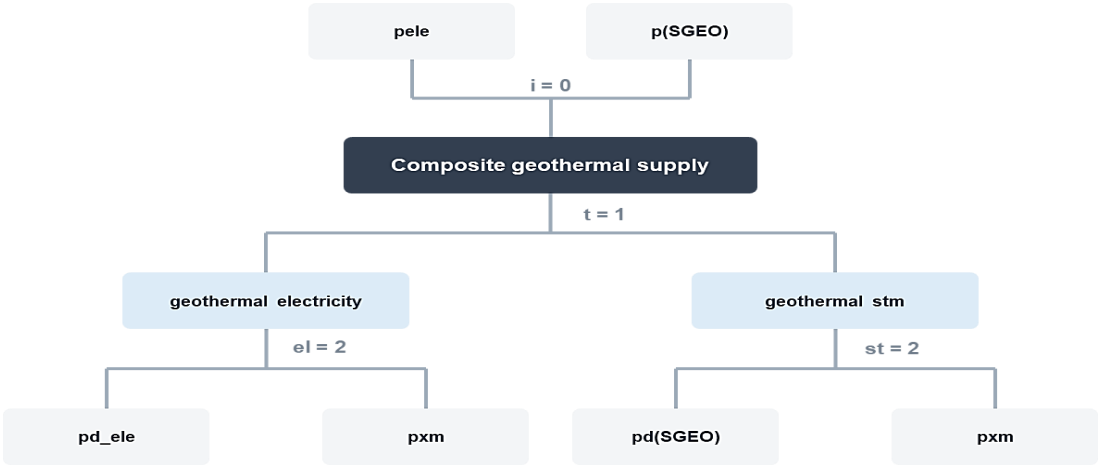


Figure 6.9. CET Nesting structure for geothermal: domestic vs. exports

6.4.4. Armington Aggregation and Electricity Pooling

The model employs a standard Armington assumption to imperfectly substitute domestic production with imports, creating a composite market price for both non-electric commodities and grid (composite) electricity as given in Table 6.13 and Table 6.14. Preceding the electricity Armington block, an intermediate wholesale pooling mechanism (eleAgg) smoothly aggregates power from distinct generation technologies (renewables, baseload/thermal and geothermal) into a unified national electricity supply as presented in Table 6.15. The nesting structures can be seen in Figure 6.10 and Figure 6.11. In the model, the elasticity of substitution between intermittent and baseload electricity is set at 3, exceeding the value of 2 commonly used in previous studies to reflect recent technological advances that have facilitated their integration into the electricity system. However, this value remains lower than the elasticity of 6 assumed among baseload technologies, as intermittent sources continue to face variability and grid integration constraints that limit their substitutability.

Table 6.13. Armington composite for non-electric commodities

```
$prod:ya(i)$nele(i)    s:1.5

    O:pa(i)                                 Q:Q0(i)

    I:pd(i)                                 Q:D0(i)
    I:pxm                                   Q:M0(i)
```

Table 6.14. Armington composite for electricity composite

```
$prod:ya_ele        s:1.5

    O:pa_ele                                Q:(sum(ele,D0(ele))+sum(ele,M0(ele)))

    I:pd_ele                                Q:(sum(ele,D0(ele)))
    I:pxm                                   Q:(sum(ele,M0(ele)))
```

Table 6.15. Aggregation (pooling) of electricity

```
$prod:eleAgg        s:3     b:6

    O:pele                      Q:(sum(ele,D0(ele) +E0(ele)))

    I:peleSW                    Q:(sum(eleRnwSoWn,D0(eleRnwSoWn) +E0(eleRnwSoWn)))
    I:peleBHO                   Q:(sum(eleBHO,D0(eleBHO) + E0(eleBHO)))   b:
    I:peleGEO                   Q:(sum(eleGeo,D0(eleGeo) + E0(eleGeo)))   b:
```

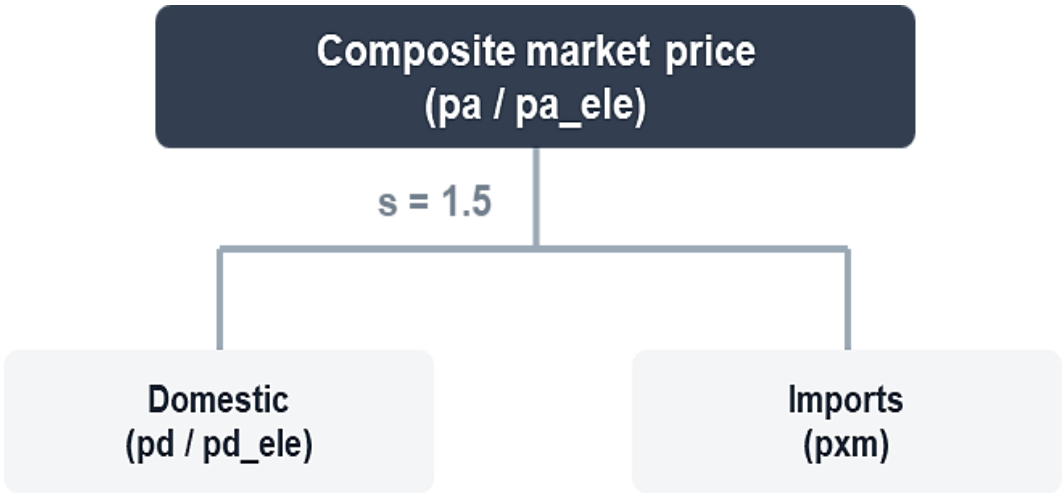


Figure 6.10. Nesting structure: non-electric commodities and electricity composite

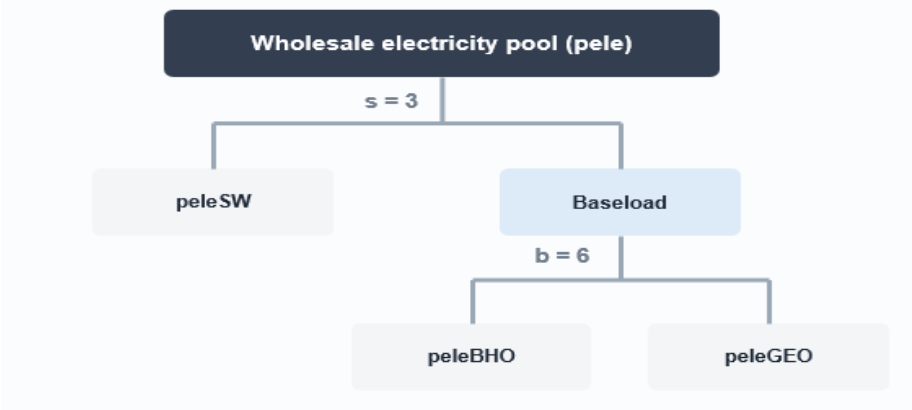


Figure 6.11. Nesting structure: electricity aggregation (pooling)

6.4.5. Consumption, Investment and Utility

The blocks in Table 6.16-Table 6.19 construct the final demand structure of the MPSGE model, transforming composite Armington market goods into macroeconomic final-use aggregates: private consumption, public consumption, investment and utility. The private consumption module separates energy and non-energy bundles to capture realistic household substitution behaviours. Government procurement and capital investment rely on rigid, single-tier aggregations. Ultimately, a top-level utility block mathematically synthesizes present private consumption and private investment (future consumption) into a single overarching welfare metric that balances the household's budget, effectively closing the macroeconomic loop.

Table 6.16. Private consumption in MPSGE model

```
$prod:yCon     s:0.25   e:1.5   ne:0.5

        O:pCon                          Q:(sum(i,C0(i)))

        I:pa(i)$(nene(i))               Q:(C0(i))     ne:
        I:pa(i)$(ene(i))                Q:(C0(i))     e:
        I:pa_ele                        Q:(CELE0)     e:
```

Table 6.17. Public consumption in MPSGE model

```
$prod:yGov   s:0.25

        O:pGov                          Q:(sum(i,CG0(i)))

        I:pa(i)$(nele(i))               Q:(CG0(i))
        I:pa_ele                        Q:(CGELE0)
```

Table 6.18. Investment in MPSGE model

```
$prod:yInv   s:0.25

        O:pInv                          Q:(sum(i,INV0(i)))

        I:pa(i)$(nele(i))               Q:(INV0(i))
        I:pa_ele                        Q:(INVELE0)
```

Table 6.19. Total welfare in MPSGE model

```
$prod:yUtil  s:0.25

        O:pU      Q:(sum(i,C0(i)) + sum(i,INV0(i)) + TAX_HOH0 - SAV_GOV0)  A:GOV
                  T:t_y

        I:pCon    Q:(sum(i,C0(i)) )
        I:pInv    Q:(sum(i,INV0(i)) - SAV_GOV0)
```

6.4.6. Final Demand and Institutional Framework

In the MPSGE model, the demand block represents the consumer's budget constraint. Consumers demand a utility good through the D: field and receive income from factor or commodity endowments specified in the E: field. The income generated from these endowments finances the consumer's demand for utility. Thus, the final macroeconomic blocks, Table 6.20 and Table 6.21, define the institutional demand and Walrasian budget constraints for the representative household (hh) and government (gov) in this model. As explicitly mapped in the budgetary flow diagrams below, these modules are not nested production functions but rather income-expenditure balancing nodes. They aggregate factor incomes, endogenous tax revenues and exogenous macroeconomic transfers, ultimately allocating the net disposable income toward aggregate utility and public consumption under a C-D demand structure. Note that the endowments are represented as the product of initial values and growth parameters. This specification is introduced to transform the model into a recursive dynamic framework, as will be discussed in detail in the following scenario analysis section. Accordingly, factor supplies are updated over time through exogenous growth paths while the calibrated benchmark structure of the economy is preserved.

Table 6.20. Demand block for households

```
$demand:hh      s:1

    D:pU                    Q:(sum(i,C0(i)) + sum(i,INV0(i)) + TAX_HOH0 - SAV_GOV0)

    E:pf(f)$(FS0(f))                Q:(FS0(f)*GrwthF(f))
    E:ptsf(eleRnw)                  Q:(TFD0_(eleRnw)*GrwthTSF(eleRnw))
    E:ptsfNuc$nucFlag               Q:(tsfNuc0*GrwthTSFnuc)
    E:pnum$TR_HOH_GOV0              Q:(TR_HOH_GOV0*GrwthTR_HOH_GOV)
    E:pxm$TR_HOH_ROW0               Q:(TR_HOH_ROW0*GrwthTR_HOH_ROW)
```

Table 6.21. Demand block for government

```
$demand:gov     s:1

  D:pGov                                Q:(sum(i,CG0(i)))

  E:pxm$TR_GOV_ROW0                     Q:(TR_GOV_ROW0*GrwthTR_GOV_ROW)
  E:pnum$TR_HOH_GOV0                    Q:(-TR_HOH_GOV0*GrwthTR_HOH_GOV)
  E:pxm$PAY_ROW_GOV0                    Q:(-PAY_ROW_GOV0*GrwthPAY_ROW_GOV)
  E:pinv                                Q:(-SAV_GOV0*GrwthSAV_GOV)
```

Following the construction of all model blocks in the MPSGE formulation, the GeoMPSGE-TR model is executed within the GAMS IDE as a Mixed Complementarity Problem (MCP) using the PATH solver. The resulting equilibrium solutions are subsequently employed to evaluate and compare the scenarios developed for this study.

6.5. Scenario Analysis and Discussion of Results

The GeoMPSGE-TR model is aligned with the Türkiye National Energy Plan 2022 (NEP), which reflects the country's long-term energy strategies and projections. To ensure a realistic analysis of national policy objectives, the fundamental inputs and boundary conditions of the model were calibrated in accordance with the forecasts and targets outlined in the aforementioned plan. The target year for assessing the impacts of various scenarios is set to 2035 since the energy plan provides a very clear and detailed snapshot for 2035 while giving only aggregated and implicit indicators beyond 2035.

To generate the projections for the target year 2035, the core static model is extended into a recursive dynamic framework. Within this structure, 2035 decisions regarding

production, consumption, savings and investment are determined based on current-period prices. Aggregate investment in 2023 is equated to the level of savings derived from the representative household's utility function. The intertemporal linkage between the two periods is governed by the capital accumulation process, which updates the capital stock by adding previous-period investment and netting out depreciation, expressed as follows:

$$K_t = I_{t-1} + (1 - \text{annual depreciation rate}) \cdot K_{t-1} \quad (34)$$

where K is the capital stock and I denote the aggregate investment. Alongside this dynamic capital evolution, the baseline growth trajectory up to 2035 is driven by exogenous macroeconomic assumptions, including labor force projections (assumed to be in line with population growth). Similarly, the growth for other exogenous variables in the model are approximated based on historical data, while technology specific factors are projected to hit NEP targets for the installed capacity and generation amounts.

Through this calibration approach, the outputs of the developed scenarios are built upon a reliable foundation that is consistent with Türkiye's current energy policies and robust in terms of system planning. The calibration process of the model is based on the following key parameters:

- The integration of the projection that Türkiye's total electricity demand will exceed 500 TWh by 2035.
- The scaling of new installed power capacities to align with the technology breakdowns and strategic targets specified in the plan, with the notable exception of nuclear power. Due to historical delays and planning uncertainties, it was assumed that nuclear installed capacity will only reach 4.8 GW, accounting solely for the Akkuyu Nuclear Power Plant which is currently in the final stages of construction and all units are planned to be gradually commissioned by 2030.

YEKDEM, as a feed-in tariff mechanism, has been one of the primary drivers of geothermal power capacity expansion in Türkiye between 2010 and 2021, as

discussed in the previous sections of this study. However, following the revisions to YEKDEM introduced in 2021 and further updated in 2023, geothermal power capacity expansion slowed markedly. While Türkiye's operational geothermal capacity increased from 14.8 MWe in 2003 to 1,691 MWe in 2023, it reached only 1,798 MWe by 2026. Although this slowdown cannot be attributed solely to the changes in YEKDEM, it nevertheless suggests that geothermal investments remain highly sensitive to revenue certainty and policy stability. This sensitivity largely stems from the distinctive characteristics of geothermal investments. Unlike solar and wind energy, whose deployment has increasingly been driven by substantial cost reductions and improved market competitiveness, geothermal energy continues to be characterized by high upfront investment costs, resource uncertainty and substantial exploration risks.

In light of the explanations provided above, maintaining effective and predictable subsidy schemes appears to be essential for sustaining future geothermal power capacity additions in Türkiye. This conclusion is also consistent with the qualitative findings presented in Chapter 4, where stakeholders largely attributed the development of the geothermal power sector to incentive mechanisms and emphasized their continued importance for future expansion. Building on these insights, the scenario analysis examines the role of subsidies in supporting further geothermal capacity expansion in Türkiye and in contributing to the achievement of the country's long-term geothermal development targets. Accordingly, two main policy scenarios for the geothermal power sector are defined within the scope of this study:

- A Baseline Scenario (BS) calibrated in alignment with the targets of the NEP,
- A set of Counterfactual Scenarios (CS) in which different incentive levels for geothermal power are analysed, i.e., subsidy levels of 10% (CS10), 20% (CS20), …, 90% (CS90).

These scenarios can be regarded as a form of sensitivity analysis with respect to different subsidy levels for geothermal power. In fact, the calibration process requires a detailed examination of numerous model parameters and alternative model structures, particularly substitution elasticities and nesting structures. At this stage,

the appropriate parameter values and nesting structure for this model were determined based on previous closely related studies.

Before comparing the Counterfactual Scenarios (CS) with the Baseline Scenario (BS), it is essential to first outline the evolution of the electricity sector from 2023 to 2035 as illustrated in Figure 6.12. It should be noted that while these results significantly overlap with the NEP findings, certain minor discrepancies exist due to a few reasons. Foremost, as noted earlier, the MPSGE model restricts nuclear capacity to a more realistic 4.8 GW. The two models employ different capacity factor assumptions for energy technologies and are calibrated to different base years. Furthermore, while the NEP model shows a decrease in the solar capacity factor over time (whereas an upward trend is typically expected), the GeoMPSGE-TR model adopts a more realistic approach. The decline observed in the NEP study might be caused by the incorporation of energy storage systems and demand-side management mechanisms, even to a limited extent.

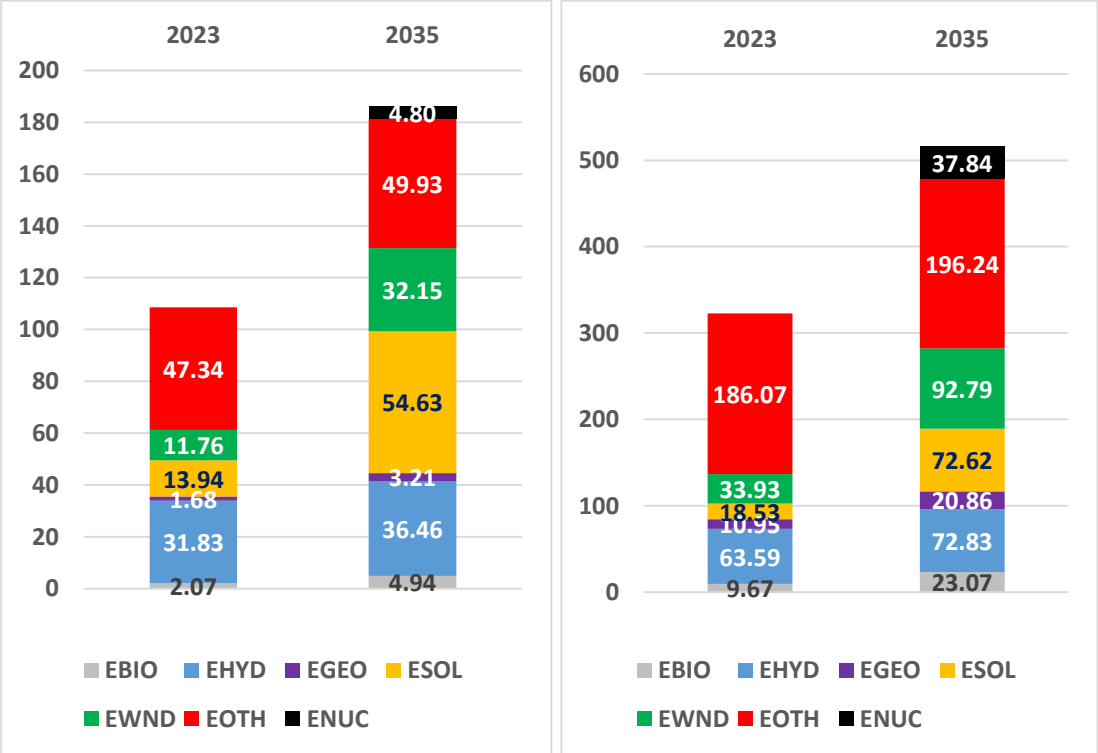


Figure 6.12. 2023 vs 2035: Installed capacities (GW) and electricity generation amounts (TWh)

Figure 6.13, on the other hand, presents the newly added capacities of each technology. As can be seen, the expansion of the electricity system is driven

primarily by solar and wind power. Although geothermal capacity grows by 90.5% over the period, its absolute increase remains limited to 1.52 GW. In contrast, solar and wind capacities increase by 40.69 GW and 20.40 GW, respectively, by 2035, underscoring their central role in meeting the projected growth in electricity demand. Furthermore, these figures suggest that both capacity additions and growth in electricity generation from fossil-fuel-based technologies will remain limited in 2035 relative to 2023 levels, reflecting the ongoing transition toward a low-carbon electricity generation mix in Türkiye.

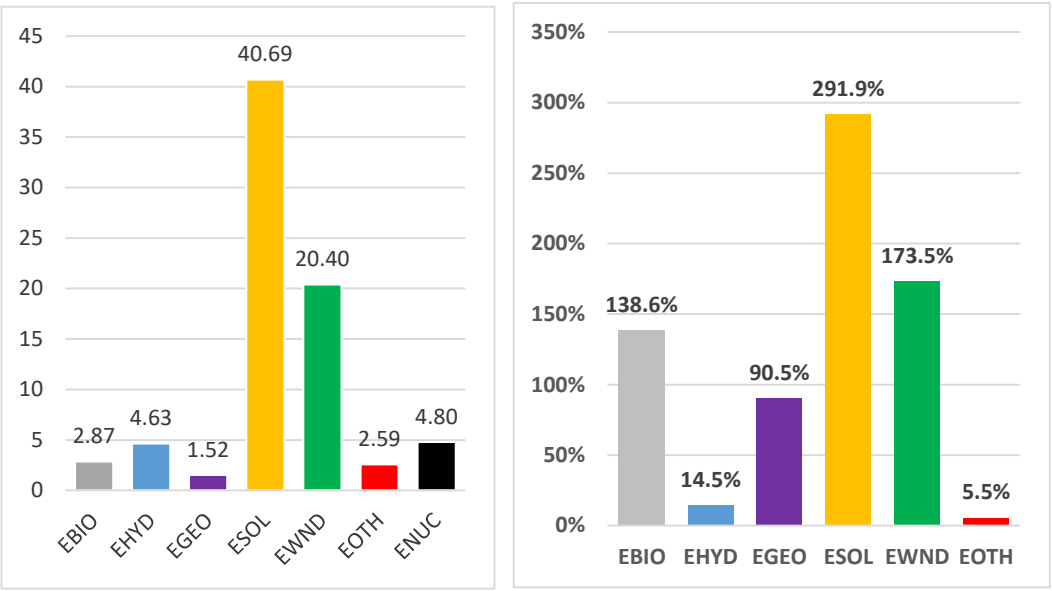


Figure 6.13. 2023 vs 2035: Newly added capacities (GW) and percentage changes (%)

As explained in the previous section, tax and subsidy coefficients are defined in the output rows of the production blocks within the MPSGE model. By modifying these values, their impacts can be evaluated relative to BS. As mentioned above, within the scope of this study, Counterfactual Scenarios (CS) are generated by varying the subsidy rates from 10% to 90% in 10% increments and the corresponding results are reported. The geothermal power capacity expansion for 2035 under different subsidy schemes is presented in Figure 6.14. The results indicate that geothermal installed capacity responds strongly to initial increases in subsidies, rising from 3.21 GW in the baseline scenario to 6.77 GW under the CS50 scenario. However, beyond this threshold, further increases in subsidies result in only modest additions to installed capacity, with capacity reaching 7.39 GW even under the CS90 scenario. This

pattern suggests that geothermal capacity growth slows considerably at higher subsidy levels, indicating that additional incentives have a limited impact on further capacity expansion as natural resource limits are gradually approached.

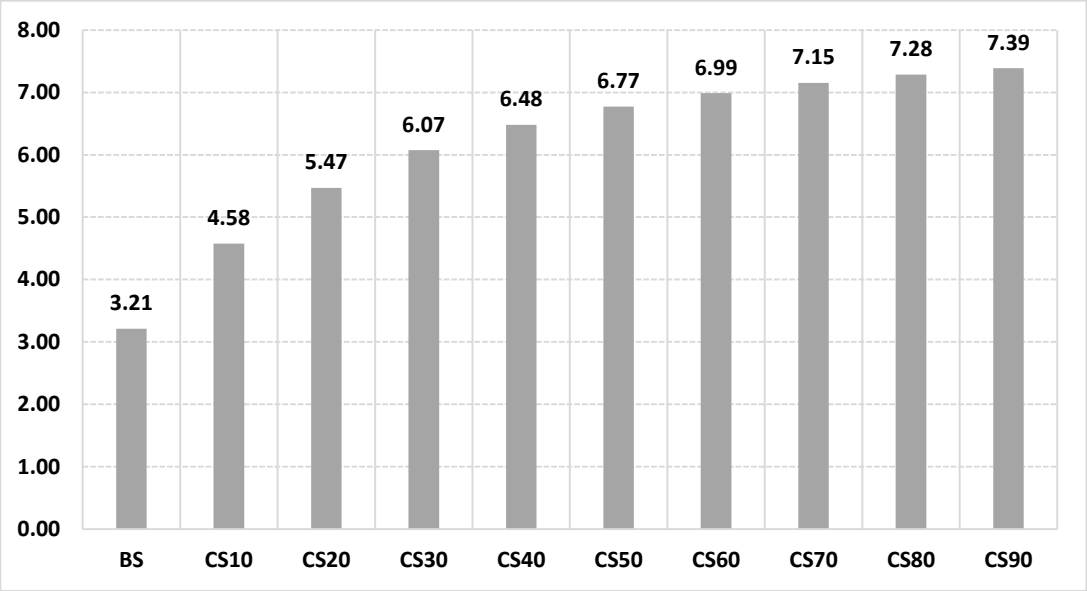


Figure 6.14. BS vs CS: Geothermal installed capacity, GW

Figure 6.15 and Figure 6.16, on the other hand, compare the Baseline Scenario (BS) and CS50 to assess the extent to which electricity generation technologies are replaced by geothermal expansion under a supportive policy framework.

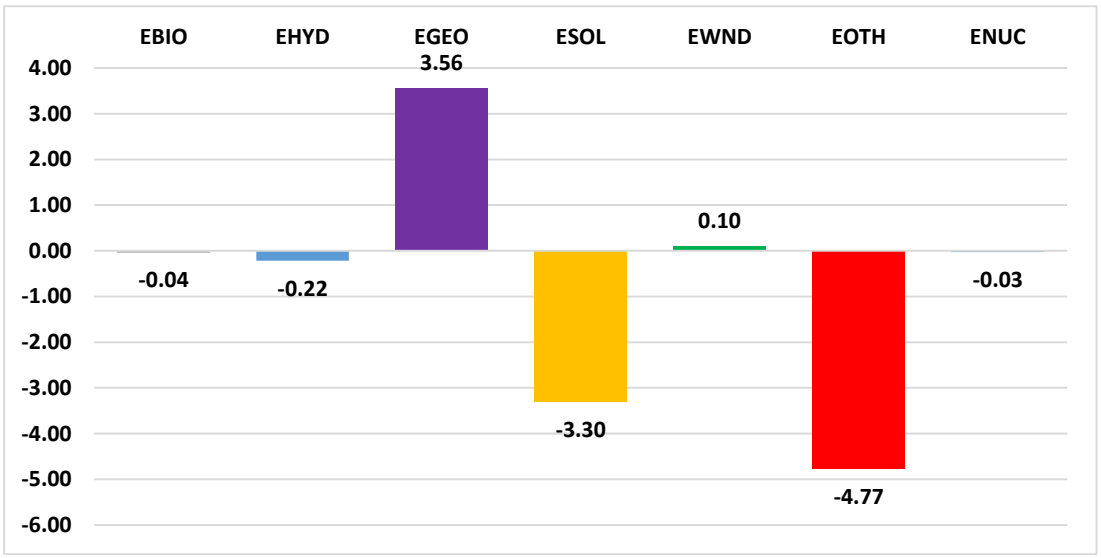


Figure 6.15. BS vs CS50: Changes in installed capacities, GW

As indicated by both figures, the increase in geothermal electricity generation primarily replaces fossil-fuel-based generation. Under the CS50 scenario, geothermal

expansion reduces fossil fuel electricity production by approximately 19 TWh in 2035, suggesting that the additional geothermal capacity is largely deployed at the expense of conventional fossil-based technologies. The results also indicate a decline in solar capacity and generation, implying that geothermal power competes not only with fossil fuels but also, to some extent, with other renewable technologies. This outcome can be attributed to the baseload characteristics of geothermal energy, which enable it to provide a more stable and continuous electricity supply than solar power.

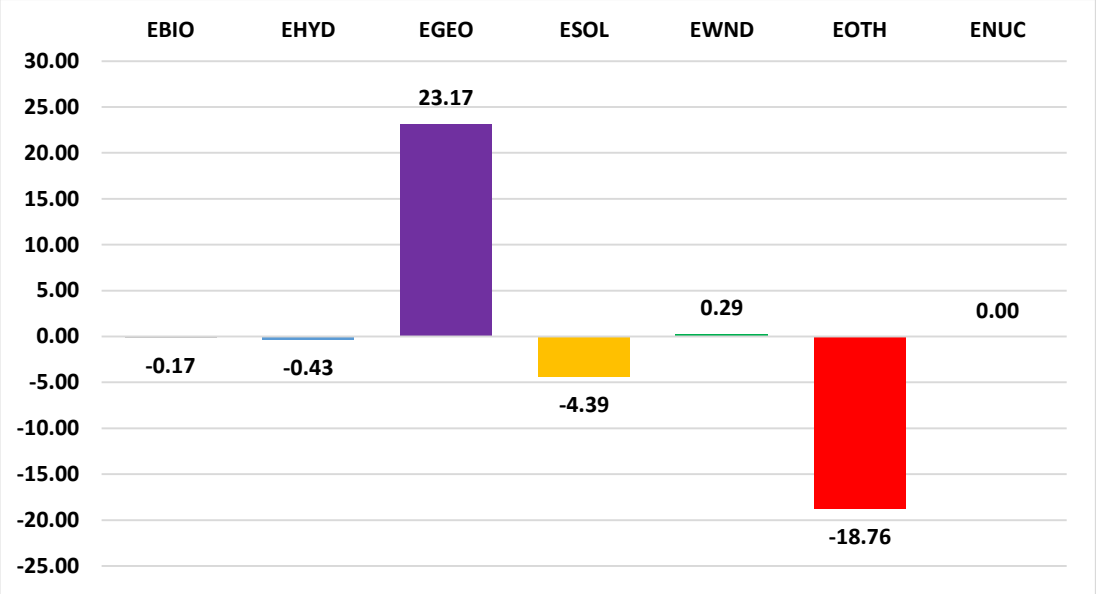


Figure 6.16. BS vs CS50: Changes in electricity generation amounts, TWh

6.6. Conclusion and Policy Implications

CGE models are frequently applied in the literature to analyze the impacts of various policy changes and the energy sector is one of the key areas in which these models have been extensively employed. Although a substantial body of CGE literature has examined the electricity sector and various electricity generation technologies, studies focusing specifically on geothermal energy remain scarce, with the existing evidence largely confined to a limited set of geographic contexts. Accordingly, developing a detailed electricity-disaggregated CGE model for Türkiye and explicitly distinguishing between geothermal power generation and geothermal heat production constituted one of the main objectives of this study.

Building on this motivation, this study constructs the GeoMPSGE-TR model and demonstrates that geothermal energy, including its power generation and heat production characteristics, can be represented in a highly detailed manner within a CGE framework, thereby contributing to the existing literature. Consequently, the scenario analyses presented in this section serve fundamentally to validate that the model functions as intended. Indeed, the model's ability to successfully replicate the 2035 NEP targets confirms its robustness and highlights its potential as a valuable tool for a wide range of future scenario analyses.

Although the scenarios conducted within the scope of this study mainly focus on the impacts of subsidies on the development geothermal power sector, the proposed modelling framework provides a foundation for future studies to undertake comprehensive policy analyses across a broad range of sectors and energy technologies. To illustrate, these studies could examine the extent to which technological progress and cost reductions make geothermal energy competitive with and without policy incentives, or assess how the use of geothermal waste heat in greenhouses affects agricultural production, prices and household welfare. Furthermore, consistent with the broader CGE literature, the GeoMPSGE-TR model enables the analysis of policy shocks across a wide range of macroeconomic indicators, including GDP, sectoral growth, employment, household income and welfare. In addition, the GeoMPSGE-TR model can be readily extended to incorporate environmental dimensions, enabling the assessment of greenhouse gas emissions, carbon intensity and other environmental indicators in response to policy changes.

Apart from its methodological contribution, this study confirms the extent to which the development of geothermal power depends on policy incentives. As evidenced by the findings presented in the previous sections, the expansion of Türkiye's geothermal power sector has been largely driven by the successful implementation of feed-in tariffs. The scenario results also suggest that further growth in geothermal electricity generation will require well-designed policy support mechanisms, particularly subsidies and other financial incentives, to overcome the high upfront investment costs and long payback periods associated with geothermal projects. The

long-term continuity of these mechanisms is equally critical, as stable policy support can strengthen investor confidence and facilitate future capacity additions.

The findings of this study also indicate that geothermal power capacity approaches a natural expansion limit even under highly generous subsidy schemes. Given the technical and resource-related limitations to further geothermal power development, future policies aimed at promoting geothermal energy should not be limited to electricity generation alone. Greater emphasis could also be placed on direct utilization applications, where Türkiye possesses considerable untapped potential. This would support the diversified utilization of geothermal resources, enabling greater economic and social benefits while improving overall resource efficiency.

Lastly, this study suggests that geothermal energy, under supportive policy frameworks, could play an increasingly important role in decarbonisation and energy security by replacing fossil-fuel-based electricity generation, while reducing import dependency and promoting economic development.

CHAPTER 7

CONCLUSION

7.1. Summary of Main Findings

Recent global energy supply shocks triggered by military conflicts have underscored the strategic importance of reducing dependence on energy imports and expanding renewable energy capacity for strengthening energy security. While renewable energy sources have played a key role in the energy transition across many countries, their intermittent and climate-dependent nature poses challenges for ensuring a reliable energy supply. On the other hand, heavy reliance on imported fossil fuels exposes countries to price volatility and geopolitical risks, while contributing to high greenhouse gas emissions. At this point, geothermal energy emerges as a domestic, reliable, non-intermittent and clean energy alternative capable of addressing these challenges. Indeed, in the aftermath of recent energy crises, geothermal energy has regained global attention, with its increased utilization becoming a strategic pillar in the future energy strategies of resource-rich countries.

Among the countries with abundant geothermal resources, Türkiye holds significant potential for power generation as well as a wide range of direct-use applications. Although the country has conducted geothermal research and exploration since the 1960s, major developments in the electricity sector began after the late 2000s, making it one of the fastest-growing geothermal electricity markets in the world over the past two decades. However, geothermal energy investments in Türkiye have shown a decreasing trend in recent years. This slowdown raises important questions about what initially drove geothermal development and which factors are now limiting its continued expansion. Thus, this thesis examines geothermal development in Türkiye and the socioeconomic impacts of its further expansion using a mixed-

methods approach that combines qualitative and quantitative techniques to provide a comprehensive, multidimensional and robust analysis. Within this integrated framework, qualitative evidence informs the quantitative analyses, while the quantitative results offer economy-wide insights that strengthen and contextualize the qualitative conclusions.

In addition to tracing the historical development of geothermal energy in Türkiye, this thesis assesses the expansion of Turkish geothermal sector using the TIS framework, focusing on its structural components, system functions and their interactions. In doing so, it contributes to the limited geothermal TIS literature by providing evidence from the Turkish case. The findings from the TIS analysis indicate that, despite remarkable growth over time, the Turkish geothermal sector has been constrained by institutional fragmentation and weak coordination among actors, limiting its ability to shape long-term policy and regulation. Functionally, international funds have played a key role in enabling resource mobilization, while YEKDEM has supported power market formation and guided investors' direction of search. However, the absence of explicit geothermal targets in policy documents still weakens both the legitimization of geothermal and investors' direction of search. In this regard, establishing geothermal-specific targets and sector-specific well-designed support mechanisms appears to be essential for sustaining investments, strengthening investor confidence and ensuring the long-term development of the geothermal sector. Similarly, the lack of a dedicated legal and incentive framework for geothermal direct use applications remains a major barrier to broader market development in the country. In addition, continued dependence on imported geothermal technologies persists despite the increased knowledge development and diffusion across the sector. Although policies promoting domestic component manufacturing have been introduced, geothermal energy remains far behind other renewable energy technologies in terms of local manufacturing capacity. Taken together, these findings suggest that while some functions have performed effectively, weaknesses in others continue to constrain the overall performance of the Turkish geothermal TIS. Although certain functions, as in the case of YEKDEM, have consistently played a dominant role in driving the development of the Turkish geothermal TIS, even minor changes in these functions still significantly slow the

development trajectory and increase the vulnerability of the whole system. This finding from the Turkish geothermal TIS further underlines the critical importance of complementarity and interaction among TIS functions in ensuring the resilience and long-term development of energy technology systems.

As a complement to the TIS analysis, this thesis also conducts semi-structured interviews with key stakeholders in the geothermal sector, providing the first comprehensive and systematic qualitative assessment of the opportunities and challenges of geothermal energy development in Türkiye. The interviews reveal conflicting priorities across participant groups, highlighting the need for more integrated policy approaches that balance the priorities and interests of all stakeholders. Among the interview findings that further inform the subsequent analyses of this thesis, while TIS analysis underscores the role of YEKDEM in stimulating geothermal investments, interviewees largely attribute the recent slowdown in the growth of the geothermal power sector to the current design of the incentive scheme. Given the high upfront investment costs, the availability of incentives and financial support remains a prerequisite for the sustainability of geothermal development. Indeed, in the Turkish case, the slowdown in geothermal investments following the revisions to YEKDEM demonstrates the continued dependence of the sector on financial support mechanisms and highlights the fragility of geothermal investments in the absence of sustained policy incentives. Similarly, uncertainty in access to financial resources significantly affects investment decisions in the sector. The TIS analysis indicates that local expertise in geothermal energy has not yet been sufficiently translated into domestic technological development through R&D activities. In line with the interview findings, leveraging Türkiye's accumulated human capital and technical expertise could help reduce the sector's dependence on imported equipment through stronger R&D support and stakeholder collaboration. On the other hand, TIS analysis reveals the fragmented structure of the geothermal power sector and participants further indicate that this pattern of market development has led to environmental problems and low social acceptance among local communities, particularly due to improper practices of small-scale and non-institutional plant operators. Another key finding from the views of stakeholders is that geothermal power plants should be designed for integrated use rather than solely

for power generation, to fully harness the potential of the geothermal resources in Türkiye and deliver additional economic and social benefits.

Although the economic benefits of geothermal direct use applications are widely acknowledged in the literature, policy documents and stakeholder interviews of this thesis, their systematic quantitative analysis has remained limited. Addressing this gap, this thesis analyses the sectoral impacts of an exogenous demand shock and increased electricity investments, including geothermal heating, through a SAM multiplier framework. As the first study to incorporate geothermal heat generation into the SAM literature, it also develops a detailed, electricity-sector-disaggregated SAM for Türkiye, providing a consistent and the most recent dataset for future research. The findings of this study highlight that under an exogenous commodity demand shock, the electricity sector, particularly renewables, emerges as a key driver of economic growth due to its strong inter-sectoral linkages. Although geothermal energy yields relatively lower economic impacts than other electricity-generation technologies when assessed solely in terms of power generation, its economic significance increases substantially when heat generation is also taken into account under alternative heat capacity and cost scenarios. The results further reveal that geothermal investments integrating heat and electricity generation, with a two-unit heat output achieved alongside a one-unit electricity investment, can surpass even wind energy, one of the most effective renewable technologies in terms of positive economic impacts, while approaching the economic performance levels of thermal energy technologies. This analysis underscores the importance of the integrated use of geothermal energy in order to fully realize its economic potential and maximize its overall economy-wide impacts for Türkiye.

Addressing the gap in the Turkish CGE literature on geothermal energy, this thesis develops the GeoMPSGE-TR model, which features a detailed representation of the electricity sector and individual electricity generation technologies, including geothermal, through technology-specific nesting structures. This methodological contribution is particularly important for conducting the analyses on Türkiye, a country endowed with substantial geothermal resources and recognized as one of the world’s leading countries in terms of geothermal energy potential. Beyond its

contribution to the Turkish literature, the explicit disaggregation of geothermal power generation and geothermal heat production advances the broader CGE literature by enabling a more detailed representation of geothermal energy. The comparison of results obtained from the GeoMPSGE-TR model with the NEP targets reveals the robustness of the model and demonstrates its potential as a reliable tool for future policy evaluation and scenario analysis. Although the GeoMPSGE-TR model is capable of analysing a wide range of alternative scenarios, this study focuses specifically on the relationship between subsidies and geothermal power expansion, as stakeholders consistently identified incentive mechanisms during the interviews as the primary driver of geothermal development in Türkiye. Accordingly, the model aims to demonstrate the extent to which future geothermal expansion depends on continued policy support. The findings confirm that sustained incentives remain crucial for expanding Türkiye's geothermal power sector. These mechanisms have been instrumental in past geothermal capacity growth, while continued long-term support will be necessary to sustain future growth. The results also demonstrate that increasing geothermal electricity generation can contribute to both decarbonisation and energy security objectives by substituting for fossil-fuel-based electricity generation. Nevertheless, geothermal power capacity appears to approach a natural growth limit even under high levels of policy support. Therefore, future policies should focus not only on electricity generation but also on direct-use applications, where Türkiye has significant untapped potential.

7.2. Policy Implications

Unlike many other renewable energy sources, geothermal energy is a versatile resource that offers a wide range of direct-use applications in addition to electricity generation. However, focusing primarily on electricity generation limits the broader utilization of geothermal resources and constrains the realization of their full potential. In this regard, despite certain similarities with other countries, Türkiye's experience offers valuable insights into geothermal energy development owing to its distinct development path. Strong policy incentives for electricity generation enabled the rapid expansion of the Turkish geothermal market and increased private sector participation. At the same time, this rapid capacity growth also gave rise to a range of

institutional, social and environmental challenges. Becoming the leading country in Europe and the fourth largest in the world in installed geothermal power capacity undoubtedly represents a remarkable achievement. However, the strong emphasis on electricity generation meant that the broader potential of geothermal resources remained largely untapped, while direct-use applications remained underdeveloped. At the same time, this experience provides a strong foundation for the next stage of geothermal development in Türkiye, where a more balanced approach combining electricity generation with direct-use applications could unlock wider economic, social and environmental benefits.

Taken together, the findings of this thesis suggest that realizing the full potential of geothermal energy in Türkiye requires a coordinated multi-level policy approach that addresses challenges at the firm, sectoral, national and supranational levels. To provide a more systematic overview of these implications, Table 7.1 synthesizes the main policy aims, recommendations and policy tools into a multi-level policy framework.

At the micro (firm and project) level, policies should primarily aim to reduce investment risks and improve project viability. Given the sector's high upfront investment costs, exploration uncertainty and long payback periods, geothermal project developers require stable and predictable financial support throughout the project lifecycle. Policy interventions should therefore focus on reducing exploration and drilling risks through dedicated national financial instruments, continued risk-sharing mechanisms, and concessional financing, while strengthening firms' technological capabilities through technical assistance, knowledge transfer and innovation support.

At the meso (sectoral) level, policies should aim to strengthen the competitiveness and innovation capacity of the geothermal sector. Particular emphasis should be placed on promoting domestic manufacturing, technological development and research and development activities to reduce costs and increase domestic value creation. Greater collaboration among industry, academia and public institutions should also be encouraged to facilitate knowledge transfer, foster technological innovation and strengthen sectoral capabilities.

At the macro (national) level, geothermal energy should be more comprehensively integrated into Türkiye's long-term energy and development strategies to accelerate sustainable geothermal deployment. Clear and explicit targets for both geothermal electricity generation and direct-use applications should be incorporated into national policy frameworks to guide future investments. Moreover, given the complex institutional structure governing geothermal projects, stronger inter-institutional coordination, or preferably a single dedicated geothermal authority, would improve licensing, permitting and overall policy implementation.

Existing support mechanisms, particularly YEKDEM, should gradually evolve from a uniform feed-in tariff scheme towards a technology-specific policy framework that rewards system reliability, flexibility, storage integration and domestic value creation. Furthermore, promoting integrated geothermal utilization and direct-use applications through national incentive schemes should become a strategic priority for maximizing the economic, social and environmental benefits of geothermal resources. Targeted incentives for waste heat utilization in existing geothermal power plants and Combined Heat and Power (CHP) requirements for new projects as part of the licensing and permitting process would improve resource efficiency and help unlock full geothermal potential.

At the same time, policies should place greater emphasis on the sustainable management of geothermal resources and environmental protection through stronger resource management, effective reinjection practices, continuous environmental monitoring and emission control mechanisms. Furthermore, stakeholder participation and public awareness through education campaigns should be promoted to strengthen social acceptance and support geothermal development at the local and national levels.

At the mega (supranational) level, stronger international cooperation can complement national efforts through long-term financing, technology transfer and research collaboration, thereby supporting geothermal innovation and the wider deployment of geothermal applications.

Table 7.1. Multi-level policy framework for geothermal energy development in Türkiye

At	Main actors	Policy aims	Policy recommendations	Policy tools
Micro Level (Firm / Project)	Project developers, investors, plant operators	To reduce project risks and improve investment viability	Support geothermal projects throughout exploration, drilling and project development; strengthen firms' technological capabilities	Exploration risk-sharing mechanisms; drilling finance; concessional loans; technical assistance, knowledge transfer and innovation support
Meso Level (Sector)	Industry associations, manufacturers, R&D institutions, universities	To strengthen sectoral competitiveness and innovation	Promote domestic manufacturing, technology development and knowledge transfer	R&D programmes; increased domestic manufacturing incentives; innovation support; enhanced industry-academia collaboration
Macro Level (National)	Government, ministries,	To accelerate sustainable geothermal deployment	Integrate geothermal electricity and heat into national energy policy through clear long-term targets and offer targeted incentives	Explicit geothermal targets; national geothermal strategy; technology-specific support schemes; revised YEKDEM
Macro Level (National)	Government, licensing authorities	To improve governance and implementation	Strengthen institutional coordination and improve project approval processes	A dedicated geothermal authority; simplified licensing; faster permitting
Macro Level (National)	Government, municipalities, local authorities	To maximize socio-economic benefits	Expand integrated and direct-use applications alongside electricity generation	Promotion of integrated geothermal utilization through national incentive schemes; CHP requirements as part of licensing and permitting process
Macro Level (National)	Environmental authorities, local communities	To ensure environmental sustainability and increase social acceptance	Improve environmental management while enhancing community support	Reinjection standards; emission control; resource monitoring; stakeholder participation and public awareness programmes
Mega Level (Supranational)	Development banks, international organizations	To mobilize international finance and technology cooperation	Support long-term geothermal investments and innovation	International financing mechanisms; technology partnerships; international R&D cooperation

Ultimately, Türkiye's geothermal experience demonstrates that rapid power capacity expansion alone is not sufficient for achieving sustainable sectoral development. Instead, realizing the full benefits of geothermal energy requires a coordinated multi-level policy framework that simultaneously addresses firm-level investment barriers, sectoral innovation, national governance and international cooperation, while integrating institutional, financial, technological, social and environmental considerations.

7.3. Future Research Opportunities

Besides evaluating geothermal energy development from a multidimensional perspective, this thesis contributes to the TIS, SAM and CGE literature not only by introducing the Turkish case but also methodologically through the development of a highly disaggregated geothermal SAM and a dedicated CGE model for evaluating geothermal policy scenarios. It also broadens the predominantly engineering-oriented Turkish geothermal literature by incorporating policy, institutional and socio-economic perspectives into the analysis. Finally, the findings provide policy-relevant insights that support evidence-based decision-making and the future development of geothermal energy in Türkiye.

Despite its novel contribution as the first comprehensive qualitative and quantitative assessment of geothermal energy, this thesis has several limitations. Although it provides inferences regarding the social and environmental implications of geothermal energy expansion, these dimensions were not directly examined through dedicated quantitative or qualitative analyses. Future research could extend the SAM and CGE models by incorporating environmental and emission-related variables, while social aspects, particularly social acceptance, could be investigated through field studies in geothermal resource-rich regions. In addition, geothermal energy development could be further examined from the growing energy justice perspective to better understand how the benefits and burdens of geothermal projects are distributed across different social groups. Another limitation concerns the availability of geothermal direct utilization data. The lack of a comprehensive national geothermal energy database, particularly reliable long-term data on direct-use

applications, constrained the scope of the quantitative analysis and limited the possibility of conducting time-series, panel data, or comparative regional analyses. Establishing such a database would support more detailed assessments of regional differences in resource characteristics, governance structures and utilization patterns. Finally, although this thesis considers geothermal development in other countries, more comprehensive international comparisons with leading geothermal countries could provide additional insights into alternative policy and development pathways.

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APPENDICES

A. SUPLEMENTARY DATA

A.1. Interview questions (In Turkish)

1. Eğitiminiz, uzmanlığınız ve deneyimizden bahseder misiniz?

2. Şu anda jeotermal enerji sektöründe hangi görevleri yürütmektesiniz?

3. Türkiye'deki jeotermal enerji sektörünü genel olarak değerlendirebilir misiniz?

4. Sizce Türkiye'nin enerji karışımı içinde jeotermal enerjinin yeri ne olmalıdır?

5. Türkiye'de jeotermal enerji potansiyelinin en yüksek seviyede değerlendirilebilmesi için ne tip araçlara ihtiyaç olduğunu düşünüyorsunuz? (daha geniş pazar, teknoloji bilgisi, destekleyici politikalar vb.)

6. Sizce jeotermal enerji santrallerinin esnekliğini artırmak için ne tür teşvik ve planlar uygulanabilir?

7. Avrupa Komisyonu tarafından Ufuk2020 çerçevesi kapsamında fonlanan GeoSmart projesinin Türkiye'de toplumsal ve sosyal etkileri sizce ne olmalı, beklenti ve görüşleriniz nelerdir?

8. GeoSmart projesinin çıktılarının kullanımına ilişkin nasıl bir geri bildirimin, ürün/süreç/hizmet geliştirme sürecinize olumlu yönde katkısı olacağını düşünüyorsunuz? (nicel veriler, nitel geri bildirim, ürün kurulum ve kullanımı vb). Bu soruyu iç ve dış paydaşlar kendi çalışma alanlarına göre cevaplandırabilirler.

9. Proje çıktılarının yaygın bir kullanım alanına kavuşması için sürecin doğal paydaşları olarak kimleri görüyorsunuz (kimler aktör ya da kurum olarak çıktıların yaygınlaşmasını sağlayabilir)?

10. Bu araştırmaya sağlıklı ve çok yönlü veri girdisi sağlamak amacı ile hangi aktörlerin dâhil edilmesi gerektiğini düşünüyorsunuz? (Spesifik kurum, isim bilgisi verilebilir)

11.(Paydaşlar açısından) Jeotermal standartları geliştirirken öncelik verilmesi gerektiğini düşündüğünüz boşluklar/alanlar nelerdir?

12. Yeni standartlar geliştirirken ticari çıkarlara en iyi şekilde nasıl hizmet edilebileceğini düşünüyorsunuz? (Paydaşların bakış açısından) Jeotermal standartları geliştirirken öncelik verilmesi gerektiğini düşündüğünüz boşluklar/alanlar nelerdir?

13. Jeotermal enerjinin toplumsal kabulü ile ilgili fikirleriniz nelerdir? Bu kabulün arttırılması gerekli midir ve gerekli ise ne şekilde arttırılabilir?

A.2. Initial GEOSAM

		ACTIVITIES																COMMODITIES																LABOR	CAPITAL	HOUSEHOLD	GOVERNMENT	CAPACC (S-I)	RoW	TOTAL
	(Billion TRY)	AGRF	MIN	FODPR	TEXCLOT	RPETR	CHE	MACHEQ	ELECTRO	OTHMAN	ELECSTEAMOC	CONS	HOTRES	TRANSCOM	FIRE	OTH	AGRF	MIN	FODPR	TEXCLOT	RPETR	CHE	MACHEQ	ELECTRO	OTHMAN	ELECSTEAMOC	CONS	HOTRES	TRANSCOM	FIRE	OTH								
ACTIVITIES	AGRF																2,377.46															189.49	2,566.95
	MIN																	491.80														81.03	572.83
	FODPR																		2,445.91													412.82	2,858.73
	TEXCLOT																			1,525.43												600.95	2,126.38
	RPETR																				497.54											272.47	770.01
	CHE																					1,397.60										582.96	1,980.56
	MACHEQ																						1,574.74									675.85	2,250.59
	ELECTRO																							726.68								408.87	1,135.55
	OTHMAN																								2,512.63							1,086.44	3,598.07
	ELECSTEAMOC																									2,897.09						4.87	2,901.96
	CONS																										6,648.81					641.58	7,290.40
	HOTRES																											1,607.01				59.79	1,666.81
	TRANSCOM																												3,853.90			958.78	4,812.67
	FIRE																													3,445.57		92.76	3,538.33
	OTH																														13,051.61	1,231.76	14,283.37
COMMODITIES	AGRF	445.04	2.34	916.31	65.16	0.02	13.31	1.26	0.18	46.40	2.55	33.33	33.28	27.69	1.37	43.35																				922.41	0.00	145.25		2,699.23
	MIN	4.44	67.43	6.11	5.13	479.89	20.37	12.06	3.27	13.32	519.62	272.83	1.91	45.27	0.99	30.45																				76.50	7.56	38.08		1,605.24
	FODPR	62.97	1.78	463.35	12.03	0.41	9.79	5.59	1.10	12.00	3.12	48.76	229.28	19.43	4.94	82.58																				2,269.43	0.00	-183.80		3,042.75
	TEXCLOT	1.22	1.06	3.21	690.88	0.07	10.99	8.54	1.67	40.19	2.15	20.88	7.24	9.26	1.89	53.08																				1,026.84	0.00	-44.43		1,834.54
	RPETR	35.51	13.05	6.02	3.50	19.75	46.29	8.83	2.50	10.88	14.03	139.64	5.64	397.85	2.22	236.32																				322.96	0.00	76.73		1,341.74
	CHE	140.56	14.68	76.11	158.84	5.03	796.35	82.33	73.37	228.39	7.29	211.10	15.48	44.51	19.53	140.36																				407.48	129.39	110.68		2,661.48
	MACHEQ	1.12	14.58	13.32	15.30	1.27	32.84	307.78	45.03	216.04	13.56	314.27	8.93	29.53	10.24	618.64																				81.64	0.00	1,660.60		3,384.69
	ELECTRO	1.03	3.78	6.67	8.28	0.79	9.55	64.30	230.68	117.22	31.87	138.10	9.94	36.89	11.09	601.42																				503.01	0.00	494.06		2,268.70
	OTHMAN	9.27	7.64	31.93	38.61	1.99	43.37	77.13	38.63	612.98	10.02	156.57	16.86	105.07	20.34	325.19																				1,435.63	6.08	1,586.22		4,523.52
	ELECSTEAMOC	19.48	29.43	45.46	79.53	13.25	42.28	39.58	12.44	66.68	1,475.46	245.96	38.94	49.18	230.69	205.51																				331.36	0.00	0.00		2,925.23
	CONS	6.53	23.02	15.29	11.40	1.08	42.62	550.46	216.43	422.07	18.63	2,262.94	12.33	29.75	50.29	245.61																				111.15	0.07	4,215.25		8,234.91
	HOTRES	0.15	0.99	2.07	2.00	0.08	1.28	2.91	0.76	4.93	1.14	16.73	39.52	9.88	5.80	140.36																				1,443.73	0.00	0.00		1,672.32
	TRANSCOM	29.10	30.49	94.65	47.21	17.19	60.82	70.43	32.03	145.98	35.17	272.92	35.09	860.24	34.96	618.64																				1,478.32	52.17	114.99		4,030.39
	FIRE	6.91	18.35	39.45	37.89	3.98	29.37	37.49	17.97	63.24	54.19	122.77	48.30	156.17	432.52	601.42																				1,938.33	10.42	0.00		3,618.77
	OTH	117.24	49.98	348.34	205.54	24.35	170.67	180.49	114.16	412.84	115.33	954.12	194.29	518.23	156.74	969.99																				3,690.30	3,380.16	1,156.84		12,859.41
	LABOR	72.83	79.53	207.39	320.95	41.40	191.81	293.53	122.71	374.78	65.68	647.59	346.62	409.71	314.48	4,266.49																									7,755.52
	CAPITAL	1,629.41	210.76	590.69	413.17	93.70	445.13	493.65	229.56	802.70	426.76	1,346.49	588.15	2,001.59	2,102.19	4,964.36																									16,338.31
	HOUSEHOLD																																7,755.52	16,338.31					24,717.96
	GOVERNMENT																-45.95	149.62	354.44	72.75	243.38	150.83	399.80	230.98	735.83	34.52	154.13	31.52	58.45	216.53	210.84				1,045.68			2,029.76	6,073.09
	CAPACC (S-I)																																		7,639.17	1,737.30			9,370.47
	RoW																308.65	1,079.95	300.28	245.24	666.04	1,191.85	920.23	846.41	1,290.74	12.34	1,670.47	35.46	129.59	104.51	601.65						130.45		9,333.82
	TOTAL	2,582.83	568.86	2,866.38	2,115.22	704.25	1,966.83	2,136.37	1,142.48	3,590.45	2,796.56	7,205.00	1,631.82	4,750.24	3,500.27	14,143.75	2,640.15	1,721.37	3,100.62	1,843.41	1,406.96	2,740.28	2,894.76	1,804.06	4,539.19	2,943.95	8,273.42	1,673.99	4,041.93	3,766.61	13,864.09	7,755.52	16,338.31	24,717.96	6,073.09	9,370.47	9,333.82	

B. APPROVAL OF THE METU HUMAN SUBJECTS ETHICS COMMITTEE

UYGULAMALI ETİK ARAŞTIRMA MERKEZİ
APPLIED ETHICS RESEARCH CENTER

ORTA DOĞU TEKNİK ÜNİVERSİTESİ
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29 EYLÜL 2021

Konu : Değerlendirme Sonucu

Gönderen: ODTÜ İnsan Araştırmaları Etik Kurulu (İAEK)

İlgi : İnsan Araştırmaları Etik Kurulu Başvurusu

Sayın Pınar Derin GÜRE

Danışmanlığını yürüttüğünüz Balkan MUTLU'nun "AB Ufuk2020 Geosmart Projesi Ön Mülakat Çalışması" başlıklı araştırması İnsan Araştırmaları Etik Kurulu tarafından uygun görülmüş ve **366-ODTU-2021** protokol numarası ile onaylanmıştır.

Saygılarımızla bilgilerinize sunarız.

[redacted]

Dr.Öğretim Üyesi Ali Emre TURGUT
İAEK Başkan Vekili

*This interview study was initiated by Balkan Mutlu as part of the GeoSmart project and was subsequently carried forward by Aysun Korucan under the supervision of Pınar Derin Güre.

C. CURRICULUM VITAE

PERSONAL INFORMATION

Surname, Name: Korucan, Aysun

EDUCATION

Degree	Institution	Year of Graduation
MS	The University of Edinburgh Energy, Society & Sustainability (with distinction)	2025
MS	METU Economics (with high honour)	2019
Minor Program	METU Economics (with high honour)	2014
BS	METU Statistics (with high honour)	2014
High School	Ayrancı High School, Ankara	2008

WORK EXPERIENCE

Year	Place	Enrollment
2016-Present	Energy Market Regulatory Authority of Türkiye (EMRA)	Energy Expert
2015-2016	Turkish Statistical Institute (TurkStat)	Assistant Expert

PUBLICATIONS

Korucan, A., Derin-Gure, P., Celebi, B., Baker, D., & Vander Velde, M. (2024). Opportunities and challenges of geothermal energy in Türkiye. *Energy for Sustainable Development, 79*, 101417. https://doi.org/10.1016/j.esd.2024.101417

Meirbekova, R., Bonciani, D., Olafsson, D. I., Korucan, A., Derin-Güre, P., Harcouët-Menou, V., & Bero, W. (2024). Opportunities and challenges of geothermal energy: A comparative analysis of three European cases-Belgium, Iceland and Italy. *Energies, 17*(16), 4134. https://doi.org/10.3390/en17164134

Korucan, A., & Okumuş, S. (2024). Kahramanmaras Earthquakes: How critical is the uninterrupted fuel supply. *Journal of International Environmental Application and Science, 19*(1), 31-45. https://izlik.org/JA36AZ72DP

Korucan, A., & Yardimci, O. (2023). Capacity Payments in the Turkish Electricity Market: A Necessity or Policy? *International Journal of Energy Economics and Policy, 13*(6), 81. https://doi.org/10.32479/ijeep.14833

Korucan, A., Türüt Aşik, S., & Akbostanci, E. (2021). Residential Energy Efficiency: Turkish Case. *Ekonomik Yaklasim, 32* (121). http://dx.doi.org/10.5455/ey.21002

PROJECTS

European Union Horizon 2020 GeoSmart Project, Grant Agreement No. 818576, Project Assistant, 2022-2024

The Scientific and Technological Research Council of Türkiye (TÜBİTAK) Funded Project: “Direct Rebound Effects of Productivity-Enhancing Projects in the Turkish Industrial Sector and Barriers and Motivations Affecting Energy Efficiency”, Project Assistant, 2020-2022

AWARDS

Energy Regulators Regional Association (ERRA), 2023 Research Award Competition-Third Prize

Research Topic: “Discussions on Capacity Mechanisms for Selected Markets in the Recent Energy Crisis”

The Edinburgh University, MSc Energy, Society & Sustainability Best Dissertation Award (Class of 2025)

Thesis Topic: Restructuring of Retail Electricity Market in Türkiye: From Liberalization to Energy Transition

PROGRAMMING SKILLS: R, GAMS, SPSS, Microsoft Office

FOREIGN LANGUAGES: Advanced in English, fluent in German and Spanish

D. TURKISH SUMMARY / TÜRKÇE ÖZET

GİRİŞ

Sürdürülebilir Kalkınma Hedefleri ve 2015'teki Paris Anlaşmasının kabulü, küresel yeşil dönüşümün gelişimi için önemli kilometre taşları olmuştur. Özellikle Kalkınma Hedefi 7, uygun fiyatlı, güvenilir ve sürdürülebilir enerjiye evrensel erişimi savunurken, Paris Anlaşması küresel ısınmayı 1,5 °C ile sınırlamayı ve 2050 yılına kadar net sıfır emisyona ulaşmayı hedeflemektedir. Bu küresel taahhütler doğrultusunda, enerji dönüşümü ülkelerin gündeminde önemli bir öncelik haline gelmiştir. Fosil yakıtların terk edilmesi senaryolarının yanı sıra, ülkeler yenilenebilir enerji kaynaklarının şebekeye entegrasyonunu sağlayacak ve enerji sistemlerinin esnekliğini artıracak yeni teknolojiler geliştirmek için bir yarışa girmiştir. Bununla birlikte, yaşanan son küresel gelişmeler, yenilenebilir enerjide büyümenin sadece çevresel bir öncelik değil, aynı zamanda stratejik bir zorunluluk olduğunu da vurgulamıştır.

85 milyonu aşan nüfusuyla Türkiye, 2024 yılında dünyanın 17. büyük ekonomisi (Dünya Bankası Grubu, 2025) ve son yirmi yılda OECD ülkeleri arasında enerji talebinde en hızlı büyümeyi kaydeden ülke olmuştur (Bulut vd., 2025). Artan elektrik talebine paralel olarak, Türkiye'nin kurulu güç kapasitesi özellikle yenilenebilir enerji yatırımlarının etkisiyle son on yılda önemli ölçüde genişlemiş ve 2014 yılındaki 69 GW seviyesinden 2024 yılında 116 GW'a ulaşmıştır (TEİAŞ, 2025). Bunun yanı sıra, Türkiye 2021 yılında Paris Anlaşması'nı onaylamış ve 2023 yılında Ulusal Olarak Belirlenmiş Katkı Beyanı'nı güncelleyerek, olağan işleyiş senaryosuna kıyasla 2030 yılına kadar sera gazı emisyonlarını %41 oranında azaltmayı taahhüt etmiş ve 2053 net sıfır emisyon hedefini yeniden teyit etmiştir (OECD, 2025).

2021 yılından bu yana Paris Anlaşması'nın bir tarafı olarak Türkiye, emisyon azaltımını hızlandırmak için uzun vadeli strateji ve eylem planlarına öncelik

vermiştir. Nitekim ülke, iki temel enerji politikası hedefi benimsemiştir: yerli enerji kaynaklarının kullanımını en üst düzeye çıkarmak ve güvenilir, uygun fiyatlı ve çevresel olarak sürdürülebilir bir enerji arzı sağlamak (Lise ve Uyar, 2022). Bu bağlamda, 2022 yılında ulusal CO_2 emisyonlarının %86,6'sını oluşturması nedeniyle enerji sektörü özel bir önem taşımakta olup emisyonların %32,6'sı ise elektrik ve ısı üretim faaliyetlerinden kaynaklanmıştır (TÜİK, 2024e). Elektrik üretiminde yerli ve yenilenebilir enerji oranını artırmak için temiz ve sürdürülebilir bir enerji stratejisine sahip olan Türkiye, 2022 yılında elektriğinin %42'sini yenilenebilir enerji kaynaklarından üretmiş ve yenilenebilir kapasitesi toplam kurulu kapasitesinin %54'ünü oluşturmuştur (EMRA, 2023a). Bununla birlikte, yenilenebilir enerjinin iklime bağlı değişkenliği, ithal fosil yakıtlara olan bağımlılığın devam etmesini gerektirmekte ve Türkiye'nin enerji güvenliğini artırma ve uzun vadeli enerji geçiş hedeflerine ulaşma çabalarını baltalamaktadır. Ülkenin yenilenebilir enerji kapasitesinde önemli bir büyüme olmasına rağmen, fosil yakıtlar hala elektrik üretiminin önemli bir bölümünü oluşturmaktadır; 2022 yılında doğal gazdan %22 ve kömürden %34 oranında elektrik üretimi gerçekleşmiştir (EMRA, 2023a). Aynı yıl, Türkiye doğal gaz ihtiyacının %99'unu (EMRA, 2023b) ve kömür ihtiyacının %61'ini (IEA, 2023) ithal etmiş, bu da ülkeyi fiyat dalgalanmalarına ve jeopolitik risklere karşı oldukça savunmasız bırakmıştır. Nitekim Rusya-Ukrayna savaşı nedeniyle 2022'de uluslararası enerji fiyatlarındaki zirveye bağlı olarak, Türkiye'nin enerji ithalat faturası Aralık 2022'de 96.548 milyon ABD dolarına ulaşmıştır (TCMB, 2025).

2022 yılında yayımlanan Türkiye Ulusal Enerji Planı'nda (2022-2035), 2020 yılında %11,7 olan elektrik üretimindeki rüzgâr ve güneş enerjisinin payının, fosil yakıtların payının azaltılması, nükleer santrallerin devreye alınması ve depolama teknolojilerine yapılan yatırımların hızlandırılmasıyla birlikte, 2035 yılına kadar kademeli olarak %34,3'e çıkarılacağı belirtilmiştir. Tüm bu uzun vadeli strateji planları, Türkiye'nin orta vadede fosil yakıtlı santrallerinden tamamen vazgeçmeyeceğini ve elektrik üretiminde kesintili enerji kaynaklarına bağlı kalmaya devam edeceğini göstermektedir; bu da jeotermal enerjinin, ülkenin düşük karbonlu enerji geçişini destekleyecek bir yenilenebilir enerji kaynağı olarak önemini vurgulamaktadır. Yerli, kesintisiz ve çevre dostu bir kaynak olan jeotermal enerji,

2010'lu yıllardan bu yana kurulu kapasitesini hızla genişleterek dünyanın önde gelen ülkelerinden biri haline gelen Türkiye için önemli avantajlar sunabilir. Birçok faydası arasında, jeotermal enerji, ülkenin elektrik ve ısı üretimi için ithal fosil yakıtlara olan bağımlılığını azaltırken, ekonomik büyümeyi, enerji güvenliğini ve çevresel hedefleri destekleyebilir.

Son yirmi yılda, Türkiye'nin işletmedeki jeotermal kurulu güç kapasitesi önemli ölçüde artarak 2003'teki 14,8 MWe'den 2023'te 1.691 MWe'ye yükselmiştir. Bununla birlikte, özellikle 2010 sonrasında jeotermal enerji piyasasında yaşanan hızlı büyümeye rağmen, son yıllarda yatırımlarda yavaşlama eğilimi gözlemlenmektedir. Bu nedenle, jeotermal enerjinin gelişimini şekillendiren temel dinamiklerin ve sektörün büyümesini sınırlayan unsurların daha iyi anlaşılabilmesi için, Türkiye'de jeotermal enerjinin tarihsel ve kurumsal gelişiminin incelenmesi ile sektörün karşı karşıya olduğu fırsat ve zorlukların ortaya konulması önem taşımaktadır. Ayrıca, farklı jeotermal genişleme senaryolarının etkilerini karşılaştırmalı analizlerle değerlendirmek, daha geniş kaynak potansiyelini ortaya çıkarmak için elzemdir. Bu doğrultuda, bu tez, Türkiye'de jeotermal enerjinin gelişimini ve sosyoekonomik etkilerini değerlendirmek amacıyla karma yöntem yaklaşımını benimsemekte; Teknolojik İnovasyon Sistemi (TİS) ve yarı yapılandırılmış mülakat analizleri gibi nitel yöntemleri, Sosyal Hesaplar Matrisi (SHM) çarpan analizi ve Hesaplanabilir Genel Denge (HGD) analizi gibi nicel yöntemlerle birlikte kullanmaktadır. Tez boyunca nitel bulgular nicel analizleri yönlendirirken, nicel bulgular bunları ekonomi genelinde değerlendirmektedir. Bu metodolojik yaklaşım, makro düzey sosyoekonomik analiz ile mikro düzey kurumsal ve paydaş perspektiflerini bütünleştirerek bulguların farklı yöntemlerle doğrulanmasına ve daha sağlam bir analiz yapılmasına olanak sağlamaktadır.

Giriş kısmı sonrasında, bu tezde Bölüm 2 küresel ve ulusal jeotermal enerji görünümüne genel bir bakış sunmaktadır. Bölüm 3, Türkiye'de jeotermal enerjinin gelişimi için TİS çerçevesini sunarken, Bölüm 4 görüşmelerden elde edilen bulguları ele almaktadır. Bölüm 5, jeotermal enerji için SHM'i geliştirmekte ve jeotermal ısıyı da içeren senaryo analizlerini sunmaktadır. Bölüm 6, GeoMPSGE-TR modelinin geliştirilmesine ve farklı teşvik senaryolarından elde edilen bulgulara

odaklanmaktadır. Son olarak, Bölüm 7, ana bulguları özetleyerek temel politika çıkarımlarını ortaya koymakta, çalışmanın kısıtlarını tartışmakta ve gelecek araştırmalara yönelik öneriler sunarak tezi sonuçlandırmaktadır.

2. JEOTERMAL ENERJİ: KÜRESEL DURUM VE TÜRKİYE

Jeotermal enerji elektrik üretiminin yanı sıra, çok geniş bir doğrudan kullanım alanına sahiptir. Temelde, orta ve yüksek sıcaklıklı jeotermal kaynaklar çoğunlukla elektrik üretiminde kullanılırken, düşük ve orta sıcaklıklı kaynaklar; ısıtma ve soğutma, banyo ve rekreasyon faaliyetleri ile çeşitli tarımsal ve endüstriyel süreçler gibi birçok doğrudan kullanım alanında yaygın olarak değerlendirilmektedir (ESMAP, 2022).

2023 yılında jeotermal elektrik, toplam jeotermal nihai enerji tüketiminin yaklaşık %20'sini oluşturmuştur (IEA, 2024). Son on yılda, küresel jeotermal kurulu kapasite neredeyse %40 artarak 2023 yılında 15.000 MW'ı aşmıştır. Bu dönemde yeni kapasite artışlarının dörtte üçünden fazlası Türkiye, Endonezya ve Kenya'ya aittir (IEA, 2024). 2023 yılında en yüksek jeotermal kurulu kapasiteye sahip ilk 10 ülkenin toplam kapasitesi 13.985 MW'a ulaşmış olup Amerika Birleşik Devletleri, Endonezya, Filipinler, Türkiye ve Yeni Zelanda, 1904 yılında ilk jeotermal elektrik santralinin kurulduğu öncü İtalya'yı bile geride bırakarak lider ülkeler olarak ortaya çıkmıştır.

Elektrik üretiminin ötesinde, jeotermal enerjinin doğrudan kullanımı da zaman içinde gelişmiş olup, bu alanda elektrik üretimindeki listeden daha farklı ülkeler ön plana çıkmıştır. 2020 verilerine göre Çin (40,6 GWth), Amerika Birleşik Devletleri (20,7 GWth), İsveç (6,7 GWth), Almanya (4,8 GWth) ve Türkiye (3,5 GWth), ısı pompaları dâhil jeotermal doğrudan kullanım kapasitesinde dünya liderleri arasında yer almaktadır (Lund ve Toth, 2021). 2020 yılı itibarıyla dünya genelindeki jeotermal ısıtma ve soğutma kurulu kapasitesi 107,4 GWth'ye ulaşmış; bu kapasitenin %72'sini jeotermal ısı pompaları oluştururken, kalan %28'lik kısmı doğrudan jeotermal ısıtma ve soğutma sistemlerinden meydana gelmiştir (Celikbilek ve Sen, 2025).

Türkiye'nin, genç faylar ve aktif volkanizma ile karakterize edilen Alp-Himalaya orojenik kuşağı üzerindeki konumu, önemli jeotermal enerji potansiyelinin temelini oluşturmaktadır (Kaya, 2012). Jeotermal kaynaklar ülkenin birçok bölgesine yayılmış olsa da, elektrik üretimi için uygun olanlar, arama ve sondaj faaliyetlerinin ağırlıklı olarak yoğunlaştığı Batı Anadolu'daki Büyük Menderes ve Gediz Grabenlerinde bulunmaktadır. Potansiyel alanların %78'i Batı Anadolu'da, %9'u Orta Anadolu'da, %7'si Marmara Bölgesi'nde, %5'i Doğu Anadolu'da ve %1'i diğer bölgelerdedir (Şimşek vd., 2005).

1984 yılında ilk jeotermal santralin devreye alınmasının ardından, Türkiye'de jeotermal kurulu güç kapasitesinin zaman içinde hızla arttığı görülmüştür. Nitekim 2020 yılında Türkiye, 2015 sonrasındaki dönemde dünyada en yüksek jeotermal kapasite artışını gerçekleştiren ülke olmuştur (Huttrer, 2021). 2023 yılında jeotermal enerji, Türkiye'nin toplam kurulu güç kapasitesinin yaklaşık %2'sini ve elektrik üretiminin %3'ünü oluşturmuştur. Türkiye'de jeotermal elektrik sektörü özellikle son yirmi yılda dikkat çekici bir büyüme sergilemiştir. 2024 yılı itibarıyla jeotermal elektrik üretimi için 67 lisansın bulunduğu ve toplam işletmedeki kurulu kapasitenin 2003 yılındaki 14,8 MWe seviyesinden 1.691 MWe'ye ulaştığı görülmüştür. Bununla birlikte, son yıllarda kapasite artış hızının önceki dönemlere kıyasla yavaşladığı dikkat çekmektedir. Özellikle 2022 itibarıyla sektörün yatırımcılar açısından görece daha az cazip hale geldiği gözlemlenmiştir. Bu durum, sektörün 2010 sonrasında teşvik mekanizmalarıyla hızla büyümesine rağmen neden yeniden durgunluk eğilimine girdiği sorusunu gündeme getirmiştir. Söz konusu yavaşlamanın yalnızca 2021 yılında YEKDEM mekanizmasında yapılan değişikliklerden mi kaynaklandığı, yoksa daha derin yapısal sorunların mı etkili olduğu sorusu, Türkiye'de jeotermal enerjinin gelişim dinamiklerini anlamak açısından kritik önem taşımaktadır.

Jeotermalin doğrudan kullanımına bakıldığında ise, ülkenin kurulu kapasitesi 2022 yılında 5.113 MWt iken, doğrudan kullanımının dağılımı termal turizm, bölgesel ısıtma, sera ısıtma, ısı pompaları ve jeotermal kurutma ve soğutma uygulamaları için sırasıyla %47,8, %27,8, %24,1 ve %0,4 olarak gerçekleşmiştir (Şener vd., 2023).

3. TÜRKİYE'DE JEOTERMAL ENERJİ GELİŞİMİNİN TEKNOLOJİK INOVASYON SİSTEMİ (TİS) ÇERÇEVESİNDE ANALİZİ

Teknolojik İnovasyon Sistemi (TİS) yaklaşımı, Carlsson ve Stankiewicz'in (1991) ortaya koyduğu "teknolojik sistemler" çerçevesine dayanmaktadır. Bu yaklaşım, Jacobsson ve Bergek (2004), Hekkert vd. (2007), Negro vd. (2007), Bergek vd. (2008a) ile Markard ve Truffer'ın (2008) katkılarıyla geliştirilerek TİS çerçevesine dönüştürülmüştür. TİS yaklaşımı, belirli bir kurumsal yapı içerisinde aktörler arasındaki dinamik etkileşimlerin bir teknolojinin geliştirilmesi, yayılımı ve kullanım süreçlerini şekillendirdiğini vurgulamaktadır. Bu çerçevede TİS; aktörler, ağlar ve kurumlar olmak üzere üç temel yapısal bileşenden oluşmaktadır.

Aktörler arasında bireyler, firmalar ve hükümet organları, finans kuruluşları, üniversiteler ve STK'lar gibi kuruluşlar yer alabilir. Bu noktada, teknik, finansal ve/veya politik olarak güçlü bir öncü aktör, teknolojinin gelişiminde önemli bir etkiye sahip olabilir veya ticari olmayan bir kuruluş, yeni teknolojilerin benimsenmesinde önemli bir rol oynayabilir (Jacobsson ve Bergek, 2004). Aktörler arasındaki etkileşimler ve işbirliği ilişkileri veya daha karmaşık bir aktörler örgütü (Wieczorek ve Hekkert, 2012) ile oluşturulan ağlar, "öğrenme" veya "politik" ağlar olarak sınıflandırılabilir. Öğrenme ağları, tedarikçiler, kullanıcılar, firmalar ve araştırmacılar arasında teknik bilginin geliştirilmesini ve yayılmasını amaçlarken, ortak inançları paylaşan farklı aktörlerden oluşan politik ağlar, politik kararları etkileme gücünü arar (Bergek vd., 2008b). Kurumlar ise, yönetmelikler, yasalar, mülkiyet hakları ve kültür ve gelenekle ilgili bazı normlar gibi resmi kuralları içerir.

TİS'in bu şekildeki yapısal analizi, araştırmacılara teknolojik geçişin gerçekleştiği koşullar hakkında bilgi edinme olanağı sağlar. Bununla birlikte, belirli politika önerilerini gerektiren bir TİS'deki temel sorunların yalnızca yapısal bileşenlere dayanarak belirlenmesi yanıltıcı olabilir, çünkü belirli bir yapısal unsurun veya unsur kombinasyonunun güçlü ve zayıf yönlerini, inovasyon süreci üzerindeki etkilerini ortaya koymadan değerlendirmek zordur (Bergek vd., 2008a; Eleftheriadis ve Anagnostopoulou, 2015). Bu nedenle, "*sistem fonksiyonları*" kavramı, TİS'in bir bütün olarak başarısını değerlendirmek için Bergek vd. (2008a), Hekkert vd. (2007)

ve Negro vd. (2007) çalışmalarında öne sürülmüş ve ampirik TİS araştırmaları için sağlam bir kavramsal çerçeve oluşturmuştur (Hsieh ve Liu, 2025).

Bir TİS'in performansı literatürde sıklıkla kullanılan belirli fonksiyonlar aracılığıyla analiz edilebilir. Bu fonksiyonlar arasında "bilgi geliştirme ve yayılımı" (knowledge development and diffusion), "girişimci deneyimleme" (entrepreneurial experimentation), "arama yönünün etkilenmesi/yönlendirilmesi" (influence on the direction of search), "pazar oluşturma" (market formation), "kaynakların harekete geçirilmesi" (resource mobilization), "meşrulaştırma" (legitimation) ve "olumlu dışsallıkların geliştirilmesi" (development of positive external economies) yer almaktadır.

TİS yaklaşımı, özellikle yenilenebilir enerji teknolojileri gibi gelişmekte olan alanların analizinde önemli bir avantaj sunmaktadır. Bu tür alanlarda piyasa ve teknoloji belirsizliklerinin yüksek olması, teknolojinin nasıl gelişeceği ve hangi aktörler tarafından benimseneceğinin önceden net olmaması nedeniyle sistem sınırlarının baştan kesin biçimde tanımlanması çoğu zaman mümkün değildir (Coenen ve López, 2010). TİS araştırmaları başlangıçta büyük ölçüde gelişmiş ülkelerdeki yenilenebilir enerji teknolojilerine odaklanmış olsa da (Kebede ve Mitsufuji, 2017), zamanla bu çerçevenin gelişmekte olan ülkelere uygulanmasına yönelik çalışmaların sayısında önemli bir artış yaşanmıştır.

Diğer yenilenebilir enerji teknolojilerinin aksine, literatürde TİS çerçevesi kullanılarak jeotermal enerjinin gelişimini inceleyen çalışmalar sınırlıdır. Bu kapsamda Leitch vd. (2019), Alberta (Kanada) örneğinde petrol ve gaz sektörünün sahip olduğu bilgi birikimi, altyapı ve kurumsal kapasitenin jeotermal enerjinin gelişimini destekleyebileceğini göstermiştir. Çalışma, TİS literatürüne mevcut ve yeni teknolojik sistemler arasındaki etkileşimleri açıklamak amacıyla "sistem tamamlayıcılığı başarısızlıkları" olarak adlandırılan yeni bir fonksiyon önermektedir.

De Jesus Fernandez ve Watson (2022), TİS'in yedi temel fonksiyonunu kullanarak Meksika'da enerji politikasındaki değişimin jeotermal ve güneş fotovoltaik teknolojileri üzerindeki etkilerini karşılaştırmalı olarak analiz etmiştir. Bulgular,

politika değişikliklerinin özellikle piyasa oluşumu ve meşruiyet işlevlerini etkilediğini; kamu yatırımlarındaki yetersizlik, insan kaynağı eksikliği ve olumsuz piyasa koşullarının ise her iki teknolojinin gelişimini sınırlandırdığını ortaya koymuştur.

Hsieh ve Liu (2025) ise Tayvan örneğinde, jeotermal kaynak potansiyeline ve iddialı politika hedeflerine rağmen sektörün gelişimini sınırlayan unsurları TİS yaklaşımıyla incelemiştir. Çalışma, sınırlı piyasa teşvikleri, yüksek maliyetler, düzenleyici engeller ve toplumsal muhalefetin jeotermal enerjinin yaygınlaşmasının önündeki temel engeller olduğunu belirlemiştir.

Jeotermal enerji geliştirme süreci; kaynak potansiyeli ve teknolojik kapasitenin yanı sıra aktörler, kurumlar, politikalar, finansal mekanizmalar ve piyasa dinamikleri arasındaki etkileşimlere bağlı karmaşık bir sosyo-teknik yapı niteliği taşımaktadır. Yeniliğin belirli bir teknoloji alanında nasıl ortaya çıktığını, yayıldığını ve olgunlaştığını sistematik biçimde inceleme imkânı sunan TİS yaklaşımı, bu sürecin analizinde önemli bir çerçeve sağlamaktadır. Bu doğrultuda çalışma, son on yılda jeotermal kurulu gücünü önemli ölçüde artırmasına rağmen son yıllarda yavaşlama eğilimi gösteren Türkiye'de jeotermal enerjinin gelişimini TİS çerçevesi kapsamında incelemektedir. Bildiğimiz kadarıyla bu çalışma, Türkiye'de jeotermal enerjiye TİS yaklaşımını uygulayan ilk araştırma olma niteliği taşımaktadır. Çalışmada, literatürde yaygın olarak kullanılan yedi temel TİS fonksiyonuna ek olarak, Leitch vd. (2019) yaklaşımı doğrultusunda petrol ve doğalgaz sektörleri ile jeotermal sektör arasındaki sistem tamamlayıcılığı sorunları da analiz kapsamına dâhil edilmektedir. Böylece çalışma, gelişmekte olan ve kaynak açısından zengin bir ülke bağlamında jeotermal enerjinin yayılımını şekillendiren kurumsal, teknolojik ve sosyal dinamiklere ilişkin kapsamlı bir değerlendirme sunmayı ve Türkiye'de jeotermal enerjinin daha etkin bir şekilde geliştirilmesine yönelik politika önerileri için analitik bir temel oluşturmayı amaçlamaktadır.

TİS yapısal analizinden elde edilen bulgulara göre, Türkiye'de jeotermal sektörü öncelikle önemli kurumsal parçalanma ve aktörler ile ağlar arasında sınırlı koordinasyon ile karakterize edilmektedir. Bu durum, güneş ve rüzgâr gibi diğer

yenilenebilir enerji sektörlerinde gözlemlenen kolektif siyasi etkinin eksikliğine yol açmakta ve uzun vadeli politika yönlendirmesi ve düzenleyici çerçevede değişikliklerde bulunma kapasitesini kısıtlamaktadır. Bu sektörel ve kurumsal yapı, özellikle jeotermal enerjinin araştırılması ve meşrulaştırılması gibi bazı temel TİS fonksiyonlarının etkinliğini de zayıflatmaktadır.

TİS fonksiyonel analizinde ortaya konulduğu üzere, mevcut jeotermal şirketleri hem ulusal hem de uluslararası platformlarda sektörel öğrenmeye, bilgi alışverişine ve girişimcilik faaliyetlerine önemli katkılarda bulunmuş olsalar da, ülkenin yerli jeotermal inovasyon kapasitesi sınırlı kalmış ve Türkiye ithal jeotermal bileşenlere büyük ölçüde bağımlı olmaya devam etmektedir. Sınırlı yerli üretim kapasitesine ek olarak, sektörel uzmanlığın Ar-Ge odaklı teknolojik gelişmeye yetersiz dönüşümü, sektörel büyümeyi engellemeye devam etmektedir.

Diğer yenilenebilir enerji kaynaklarının aksine, ulusal enerji politikası belgelerinde jeotermal enerjiye özgü açık hedeflerin bulunmaması, gelecekteki teknolojik ve pazar öncelikleri konusunda zayıf sinyaller verdiği için yatırımcı arayışının yönünü baltalamaktadır. Jeotermal enerjiyi doğrudan hedefleyen uzun vadeli politikaların geliştirilmesi, sektörel ağları önemli ölçüde güçlendirebilir, paydaşlar arasında beceri ve uzmanlığın yayılmasını teşvik edebilir ve jeotermal enerjinin hem ulusal hem de yerel düzeyde meşruiyet kazanmasına katkıda bulunabilir.

Yüksek başlangıç sermaye gereksinimi nedeniyle jeotermal enerji yatırımları, büyük ölçüde finansal destek mekanizmalarının varlığına bağlılığını sürdürmektedir. Türkiye örneğinde, uluslararası fonlar, kaynak mobilizasyonunu sağlayan bir risk azaltma mekanizması olarak işlev görerek jeotermal enerjinin hızlı yayılımında önemli bir rol oynamıştır. Öte yandan, daha önce jeotermal enerji kapasitesi genişlemesinin ve yatırımcı güveninin temel itici gücü olarak hizmet veren YEKDEM, artık pazar gelişimini kısıtlayan bir unsur olarak hareket etmektedir. Bu durum, mevcut teşvik şemasının, gelişen pazar dinamiklerini ve jeotermal sektöre özgü teknolojik gelişmeleri daha iyi yansıtacak şekilde revize edilmesi ihtiyacını vurgulamaktadır.

Jeotermal enerjinin doğrudan kullanım uygulamaları için yasal bir çerçeve ve ulusal bir teşvik şemasının olmaması, ülkede kaynak mobilizasyonu, stratejik yönlendirme

ve pazar gelişimi için önemli bir engel teşkil etmektedir. Sonuç olarak, artan finansal belirsizlik, jeotermal projelerin doğasında var olan risklerle birleştiğinde, yüksek başlangıç maliyetleri nedeniyle yatırımcıları yeni yatırımlar yapmaktan caydırmaktadır. Piyasa oluşumunda bir başarısızlık olarak, ülkenin petrol ve doğalgaz sektörlerinde yıllar içinde biriktirdiği kapsamlı teknik uzmanlığa rağmen, bu birikimin jeotermal uygulamalar için sistematik olarak yaygınlaştırılamaması, esas olarak destekleyici düzenleyici çerçevelerin yokluğundan kaynaklanmaktadır.

4. TÜRKİYE'DE JEOTERMAL ENERJİ GELİŞİMİNDE FIRSATLAR VE ZORLUKLAR

Türkiye'de jeotermal sektörü özelinde yarı yapılandırılmış görüşmelere dayalı gerçekleştirilen ilk kapsamlı ve sistematik nitel analiz olma özelliğini taşıyan bu çalışma, önceki TİS bölümüne tamamlayıcı olarak, jeotermal enerji sektörünün karşılaştığı zorlukları belirlemeyi ve potansiyel çözümler önermeyi amaçlamaktadır.

Araştırmanın amacı doğrultusunda, çalışmada nitel araştırma yöntemlerinden yarı yapılandırılmış mülakat tekniği kullanılmıştır. Nicel ve nitel araştırma yöntemleri veri toplama, örneklem seçimi ve analiz süreçleri bakımından farklılık göstermektedir. Nicel araştırmalar genellikle deney, anket ve yapılandırılmış görüşmeler gibi yöntemlerle büyük örneklemlerden veri toplayarak istatistiksel analizlere dayanırken; nitel araştırmalar açık uçlu görüşmeler, gözlem ve belge incelemesi gibi yöntemlerle olguları derinlemesine anlamayı amaçlamaktadır (Gerring, 2017). Bu nedenle nitel araştırmalarda örneklem büyüklüğünden ziyade araştırma sorusuna en uygun katılımcıların seçilmesi önem taşımaktadır. Bu kapsamda yaygın olarak kullanılan amaçlı örnekleme, araştırma problemine ilişkin zengin bilgi sağlayabilecek bireylerin seçilmesini esas almaktadır (Creswell, 2009). Amaçlı örnekleme kapsamında kolaylık, homojen, kartopu ve tipik/aykırı durum örneklemesi gibi farklı tekniklerden yararlanılabilmektedir (Gelo vd., 2008).

Nitel araştırmalarda yarı yapılandırılmış görüşmeler, en yaygın veri toplama yöntemlerinden biridir. Bu yöntemin temel amacı, araştırma konusu hakkında bilgi ve deneyime sahip katılımcılardan derinlemesine veri toplamaktır. Ayrıca

araştırmacının konuya ilişkin ön bilgi ve varsayımlarını, katılımcıların deneyim ve algılarıyla karşılaştırmasına olanak sağlamaktadır (Horton vd., 2004). Yarı yapılandırılmış görüşmeler, önceden hazırlanmış açık uçlu sorulara dayanmakla birlikte, yapılandırılmış görüşmelerden farklı olarak görüşmenin akışına göre yeni soruların yöneltilmesine ve belirli konuların daha ayrıntılı ele alınmasına imkân tanır. Bu esneklik sayesinde katılımcıların görüş ve deneyimlerine ilişkin kapsamlı ve zengin veriler elde edilebilmektedir (Barriball ve While, 1994).

Bu çalışmada, Türkiye'de jeotermal enerji gelişimine yönelik fırsatları ve zorlukları belirlemek amacıyla, Aralık 2021 ile Ocak 2023 tarihleri arasında 21 katılımcıyla yarı yapılandırılmış görüşmeler yapılmıştır. Görüşme yapılacak kişilerin nihai listesini oluşturmadan önce, literatür taramasına dayanarak jeotermal enerji sektörü için farklı rolleri, ilgi alanları ve yetkileri olan kilit gruplar araştırılmıştır. Görüşmeler için birincil katılımcılar, paydaş haritalaması kapsamında oluşturulan güç-ilgi matrisi kullanılarak belirlenmiş ve ilk aşamada 15 kişi seçilmiştir. Daha sonra kartopu örnekleme tekniğiyle ek katılımcılar araştırmaya dâhil edilmiştir. Bu süreç sonunda, beş farklı paydaş grubunu temsil eden toplam 21 katılımcıya ulaşılmış ve mülakatlar yapılmıştır.

Mülakat soruları nihai hale getirilmeden önce bir ön soru seti hazırlanmış ve akademisyenler, araştırmacılar, santral işletmecileri ile bankacılık sektörü temsilcilerinin katılımıyla çevrim içi bir ön değerlendirme toplantısı gerçekleştirilmiştir. Bu toplantıda sorular geçerlilik ve uygunluk açısından değerlendirilmiş, alınan geri bildirimler doğrultusunda revize edilerek nihai mülakat soruları oluşturulmuştur. Toplam 18 (5 tanesi teknik ve bu çalışma kapsamında olmamak üzere) açık uçlu sorudan oluşan mülakat formu; katılımcıların Türkiye'de jeotermal sektörünün mevcut durumu, enerji politikalarındaki rolü, sunduğu fırsatlar, gelişimini sınırlayan engeller, politika önerileri ve jeotermal enerjinin toplumsal kabulüne ilişkin görüşlerini ortaya koymayı amaçlamaktadır.

Görüşme formu, katılımcıların sorulara önceden aşina olmalarını sağlamak amacıyla mülakat öncesinde e-posta yoluyla paylaşılmıştır. Katılımcıların uygunluk durumuna göre çevrim içi gerçekleştirilen görüşmeler yaklaşık 60-90 dakika sürmüştür.

Görüşmeler öncesinde katılımcılara tüm verilerin gizli ve anonim olarak değerlendirileceği bildirilmiş, ses kayıtları ise katılımcıların onayı alınarak transkripsiyon ve analiz amacıyla gerçekleştirilmiştir.

Çalışmada, görüşme verilerindeki temel temaların belirlenmesi ve yorumlanmasını kolaylaştırmak, aynı zamanda altta yatan anlamları keşfetmek ve katılımcıların deneyimlerini ve bakış açılarını yakalamak için "tematik analiz" benimsenmiştir. Öncelikle, literatür taraması ve araştırma amaçlarına dayalı olarak tümdengelimsel bir kodlama şeması geliştirilmiş, ardından görüşme verilerinden ortaya çıkan temaları yakalamak için tümevarımsal bir yaklaşımla kod şeması yinelemeli olarak iyileştirilmiştir. Karmaşık kodlama sürecine sistematik bir yaklaşım sağlamak için, bu araştırmada nitel veri analiz aracı olarak MAXQDA 2022 kullanılmıştır.

MAXQDA tarafından önerilen kodlama aracı kullanılarak, görüşmeler sırasında jeotermal enerji ile ilgili en çok dile getirilen konular "fırsatlar" ve "zorluklar" olarak belirlenmiştir. Fırsatlar ayrıca "mevcut" ve "gelecek" olarak sınıflandırılırken, zorluklar literatürdeki benzer çalışmalarla uyumlu olarak dört kategori altında gruplandırılmıştır: "politik/düzenleyici/kurumsal", "çevresel/sosyal", "finansal/ekonomik" ve "teknik". Bu ana kodlama kategorilerine ek olarak, görüşme verilerinin farklı yönlerini daha iyi anlamak için her kategori altında çeşitli alt kodlar da geliştirilmiştir. Buna göre, katılımcıların her ifadesi ilgili kodlama öğesiyle eşleştirilmiş ve her öğe ve kodlama kategorisi için kodlama frekansları elde edilmiştir.

Mülakatların analizi ile çalışma sonunda elde edilen genel çıkarımlara bakıldığında, paydaşların farklı zorluk ve fırsatlara yoğunlaştığı görülmüş ve bu durum paydaş perspektiflerinin çeşitliliğini ortaya koyarak farklı paydaşların beklenti ve önceliklerini dengeli biçimde gözeten daha bütüncül politika yaklaşımlarına duyulan ihtiyacı vurgulamıştır.

Görüşmelerden elde edilen bulgular, Türkiye'nin yeni teknolojilerin ve mevcut bilgi birikiminin entegrasyonuyla daha da geliştirilebilecek önemli bir jeotermal potansiyeline sahip olduğunu göstermiştir. Bununla birlikte, ülkede jeotermal enerji

geliştirme çalışmaları siyasi, düzenleyici ve kurumsal; mali ve ekonomik; teknik ve çevresel ve sosyal engellerle kısıtlanmaya devam etmektedir.

Kurumsal ve düzenleyici engeller arasında, dağınık bir pazar yapısı, kurumlar arası koordinasyonun zayıf ve izin süreçlerinin uzun ve yorucu oluşu, doğrudan kullanım uygulamalarının yetersiz gelişimi ve yetersiz izleme ve denetimler öne çıkmaktadır. Finansal kısıtlamalar öncelikle yüksek başlangıç yatırım maliyetleri, mevcut YEKDEM tasarımı ve doğrudan kullanıma yönelik teşviklerin olmamasıyla bağlantılıdır. Teknik açıdan, mevcut teknik eksikliklerin yanı sıra, daha fazla teknolojik gelişme, bilgi geliştirme ve sürdürülebilir rezervuar yönetimi ihtiyacı devam etmektedir. Jeotermal enerjinin düşük sosyal kabulü en önemli çevresel ve sosyal engel olarak öne çıkmaktadır.

Görüşmelerden elde edilen bilgiler ışığında, Türkiye'nin özellikle son on yıllarda önemli bir ivme kazandıktan sonra jeotermal enerjinin sürdürülebilir gelişimine politika yapıcılarca ayrıca öncelik verilmesi gerektiği sonucuna varılmıştır. 2021 yılında YEKDEM'de yapılan ve santral işletmecileri için getirileri azaltan değişikliklerin ardından jeotermal enerji sektöründe gözlemlenen yavaşlama, jeotermal yatırımları çekmek için finansal desteğin kritik önemini vurgulamaktadır. Önemli potansiyeline rağmen, jeotermal enerji, diğer yenilenebilir enerji kaynaklarına kıyasla yüksek başlangıç yatırım maliyetleri nedeniyle daha fazla teşvik gerektirmektedir. Ayrıca, sık sık değişen politikalar ve ülkedeki mevcut ekonomik koşullardan kaynaklanan belirsizlik, jeotermal yatırımların gidişatını belirleyen önemli bir faktördür.

Jeotermal enerjinin doğrudan kullanımı Türkiye'nin birçok bölgesinde mümkündür ve bu kullanım ısıtma için doğal gaza bağımlılığı azaltmak, bölgesel kalkınmayı desteklemek, yerel istihdam yaratmak ve sosyal kabulü artırmak gibi önemli avantajlar sunabilir. Bu bağlamda, doğrudan kullanıma yönelik yeni finansal teşviklerin hayata geçirilmesi veya tesis işletmecilerine jeotermal enerjinin entegre kullanımını zorunlu kılan düzenlemeler getirilmesi, doğrudan kullanım uygulamalarının daha yaygın biçimde benimsenmesini önemli ölçüde teşvik edebilir.

Türkiye, jeotermal enerji alanındaki birikmiş insan sermayesi ve uzmanlığından yararlanarak ithal ekipmanlara olan bağımlılığını azaltabilir. Bu, Ar-Ge faaliyetlerine verilen desteğin artırılması, yatırımcılar ve araştırmacılar arasında bilgi alışverişinin geliştirilmesi ve paydaşlar arasında daha güçlü iş birliği ile daha da hızlandırılabilir.

Bürokratik süreçleri ve yatırımcılar ile arazi sahipleri veya yerel topluluklar arasındaki çatışmaları en aza indirmek için, görüşmeler sırasında sıklıkla vurgulandığı üzere, jeotermal enerjinin merkezi bir kurum altında yönetilmesi kritik önem taşımaktadır. Bu, yatırımcıların devam eden projeleri daha verimli bir şekilde uygulamalarını ve daha fazla yatırımı teşvik etmelerini de sağlayabilir. Daha sıkı ve sistematik izleme mekanizmaları, kâr odaklı tesis işletmecilerinin uygunsuz uygulamalarından kaynaklanan çevresel hasarı önlemede ve rezervuar sürdürülebilirliğini korumada önemli bir rol oynayabilir.

Artan ekonomik ve sosyal faydalar, azaltılmış çevresel etkilerle birleştiğinde, yerel topluluklar arasında jeotermale karşı daha olumlu tutumlar geliştirebilir ve zaman içinde yeni projelere karşı direnci önemli ölçüde azaltabilir. Dahası, proje uygulamasına başlamadan önce yerel paydaşlarla sürekli diyalog ve şeffaf bilgi paylaşımı yoluyla topluluk katılımını teşvik etmek ve jeotermal enerjiyi okul müfredatına entegre etmek, Türkiye'de kaynağa yönelik kamuoyu farkındalığını ve sosyal kabulü önemli ölçüde artırabilir.

5. TÜRKİYE JEOTERMAL ENERJİ SEKTÖRÜ İÇİN SOSYAL HESAPLAR MATRİSİNİN OLUŞTURULMASI VE ÇARPAN ANALİZİ

Bu bölüm, Türk jeotermal enerji sektörü için bir Sosyal Hesaplar Matrisi (SHM) oluşturmakta ve dışsal bir emtia talebi şokunun ve jeotermal ısıtma da dâhil olmak üzere artan elektrik yatırımlarının sektörel etkilerini incelemektedir.

SHM'nin kökenleri, 1960'ların başlarında Richard Stone ve Alan Brown tarafından başlatılan Cambridge Büyüme Projesi'ne dayanmaktadır. Bu çalışma için ilk SHM'nin oluşturulmasının ardından, Pyatt ve Thorbecke (1976) SHM kavramını formüle etmiş ve politika ve planlama amaçları için resmi bir çerçeve sunmuştur.

Pyatt ve Round (1977), Pyatt ve Round (1979), Defourny ve Thorbecke (1984) ve Thorbecke (1995) gibi diğer erken dönem çalışmalar da SHM literatürünün hızlı gelişimine önemli katkılarda bulunmuştur.

Bütüncül bir veri tabanı olarak SHM, belirli bir zaman diliminde ekonomik aktörler arasındaki tüm ekonomik işlemleri ve gelir transferlerini göstermektedir. Hem sosyal hem de ekonomik verileri içeren SHM, girdi-çıktı tablolarından ve standart ulusal hesaplardan daha geniş kapsamlıdır. Thorbecke (2000), SHM'nin belirli bir yıl için sosyoekonomik dinamiklerin ayrıntılı ve ayrıştırılmış bir resmini sunduğunun altını çizmektedir. Coğrafi kapsam açısından, SHM ulusal, bölgesel veya alt bölgesel düzeylerde oluşturulabilir. SHM için katı veri derleme gereksinimleri olmamasına rağmen; girdi-çıktı tabloları, ulusal hesaplar, kamu maliyesindeki tamamlayıcı veriler ve ulusal gelir hesaplarından elde edilen veriler, SHM'nin ana veri kaynaklarını oluşturmaktadır (Erdoğan, 2011). Nitekim yalnızca ara girdilerin akışı yoluyla sektörel bağlantıları gösteren girdi-çıktı tabloları, hanehalkları, hükümet ve dış alem (RoW) gibi diğer kurumlar arasındaki gelir ve harcama akışlarını da kapsayacak şekilde genişletilebilir (Reinert ve Roland-Holst, 1997). SHM, makro bir bakış açısını piyasaların ve kurumların daha ayrıntılı bir tanımıyla birleştiren orta düzey bir çerçeve sunmaktadır (Round, 2003).

Kare matris olarak SHM'nin her satırı ve sütunu "hesap" olarak adlandırılır ve satırlar ilgili sektör veya kurumun gelirlerini (tahsilatlarını) gösterirken, sütunlar giderlerini (ödemelerini) gösterir. Çift girişli muhasebe ilkesine göre, bir hesap için satır ve sütunların toplamı eşit olmalıdır, yani her hesap için toplam ödeme toplam tahsilata eşit olmalıdır (Breisinger vd., 2010). Bu çalışma için oluşturulan SHM, temelde yedi hesaptan oluşmaktadır: faaliyetler, mallar, üretim faktörleri (emek ve sermaye), hanehalkı, hükümet, yatırım (tasarruf) ve dış âlem hesabı (RoW).

Faaliyetler, mal ve hizmet üreten, yani emtia üreten varlıklardır. Üretim sürecinde, ara malların satın alınmasına harcama yaparlar ve katma değeri üretim faktörlerine dağıtırlar. Bu faaliyetler tarafından üretilen mallar iç pazara arz edilir ve/veya ihraç edilir. Öte yandan, emtialar hem iç üretim hem de dış pazarlar (ithalat) tarafından karşılanır ve devlete ödenen dolaylı vergilere tabidir. Bu emtialar, ara girdi talebi,

tüketim (özel ve kamu) ve yatırım (özel ve kamu) olmak üzere toplam iç talebi karşılar. Hanehalkları, üretim faktörlerinin sahipleri olarak ücret ve kar şeklinde gelir elde eder ve hükümetten ve dış âlemden transfer ödemeleri alır. Daha sonra emtia satın alırlar, doğrudan devlete vergi öderler ve özel tasarruf yaparlar. Doğrudan ve dolaylı vergi gelirleri ve yurtdışından gelen transferler, devlet gelirini oluşturur. Devlet bunu emtia satın almak, hanehalkına transfer yapmak, yabancı borçlanma faiz ödemeleri yapmak ve kamu tasarrufu yapmak için kullanır. Aslında, özel ve kamu tasarrufları yatırım harcamaları olarak hizmet eder. Son olarak, dış âlem ithalattan ve devlet faiz ödemelerinden gelir elde eder ve bunu ihracat ödemeleri, hane halklarına yapılan yabancı havaleler ve yabancı tasarrufların devlete aktarılması için kullanır.

GEOSHM'nin (çalışmada oluşturulan SHM bundan sonra GEOSHM şeklinde anılacaktır) genel yapısı belirlendikten sonra, bir sonraki adım "Faaliyetler" hesabına dâhil edilecek sektörleri belirlemektir. Bu çalışmanın temel odağı jeotermal enerji sektörü olduğundan, girdi-çıktı tablosunda yer alan 64 sektör, jeotermal endüstriye girdi sağlayan veya sektörün çıktılarını kullanan 15 sektör altında toplulaştırılarak GEOSHM sektörleri kapsamında ele alınmıştır. GEOSHM'nin oluşturulmasında, TÜİK tarafından yayımlanmış en güncel 2023 yılı girdi-çıktı tablosuna ek olarak; ödemeler dengesi istatistikleri, kamu gelir ve harcama verileri ile sosyal güvenlik kurumu istatistikleri gibi çeşitli idari veri kaynaklarından yararlanılmıştır. Başlangıç GEOSHM'i oluşturulduktan sonra, satır ve sütun toplamlarının eşitliğini sağlamak amacıyla öncelikle Kılınç'ın (2022) çalışmasında benimsenen RAS ve en küçük kareler yaklaşımına dayalı doğrusal olmayan optimizasyon modeli kullanılarak dengeleme işlemi uygulanmıştır. Sonrasında, "Elektrik, gaz, buhar ve iklimlendirme" sektörü ilave bir ayrıştırmaya tabi tutulmuş; söz konusu sektör "elektrik" (biyokütle, hidroelektrik, güneş, rüzgâr, jeotermal ve termal), "buhar/ısı" (jeotermal ısı ve diğer ısı) ve "gaz" olmak üzere üç alt gruba ayrılmıştır. Bu ilave ayrıştırmadan kaynaklanan herhangi bir tutarsızlık ortaya çıkması ihtimaline karşın GEOSHM yeniden dengelenmiştir.

Enerji teknolojilerine odaklanan SHM çalışmaları incelendiğinde, jeotermal enerjiye yönelik araştırmaların oldukça sınırlı olduğu görülmektedir. Bu alandaki önemli çalışmalardan Hartono vd. (2020a), Endonezya'da kömür ve çeşitli yenilenebilir

enerji santrallerine yönelik 1 GW'lık yatırımların ekonomik, istihdam ve çevresel etkilerini simüle etmiştir. Bulgular, jeotermal ve rüzgâr enerjisi yatırımlarının yüksek yatırım maliyetlerine rağmen en yüksek GSYİH ve istihdam artışını sağladığını, jeotermal yatırımların ise madencilik, inşaat, enerji, ulaşım ve finans gibi birçok sektörde ekonomik canlanmayı desteklediğini göstermektedir. Benzer şekilde, Azzahrah vd. (2023), Endonezya'da hidroelektrik, biyoyakıt ve jeotermal enerji yatırımlarını karşılaştırmış ve jeotermal enerji santrallerinin GSYİH, istihdam, hanehalkı geliri ve CO_2 emisyonlarındaki değişim açısından en yüksek etkiyi yarattığını ortaya koymuştur.

Jeotermal enerjiye yönelik SHM çarpan analizi çalışmalarının farklı ülke bağlamlarında oldukça sınırlı olması nedeniyle, bu çalışma Türkiye örneğinden elde edilen bulgularla literatüre önemli bir katkı sunmayı amaçlamaktadır. Ayrıca, elektrik sektörünün detaylı ayrıştırılması, özellikle jeotermal enerji sektörünün jeotermal elektrik ve jeotermal ısı üretimi olarak ayrılması için benimsenen metodolojik yaklaşım, enerji tabanlı SHM çarpan analizine yeni bir boyut kazandırmaktadır. Bildiğimiz kadarıyla, bu araştırma jeotermal ısı üretimini açıkça bir SHM çarpan çerçevesine dâhil etme girişiminin ilk örneğidir. Son olarak, bu çalışma kapsamında oluşturulan SHM, gelecek Türkiye odaklı enerji temelli HGD model uygulamaları için güncel, kapsamlı ve yüksek düzeyde ayrıştırılmış bir veri altyapısı sağlayarak önemli bir referans niteliği taşımaktadır.

Çalışmada esas olarak iki farklı senaryo grubu ile ekonomide ortaya çıkacak doğrudan, dolaylı ve uyarılmış etkiler hesaplanarak sektörel ve enerji teknolojileri bazında karşılaştırmalar yapılmıştır.

Senaryoların ilk bölümü, sektörler genelinde dışsal bir şoktan kaynaklanan emtia talebindeki bir birimlik artışın doğrudan, dolaylı ve uyarılmış etkilerini incelemektedir. Elektrik sektörü açısından, elektrik talebindeki bir birimlik artışın elektrik üretiminde karşılık gelen bir birimlik artışla karşılandığı varsayılmıştır. Alternatif senaryolarda ise bu ilave elektrik talebinin yalnızca güneş, jeotermal veya rüzgâr gibi tek bir enerji kaynağı tarafından karşılandığı kabul edilmiş; böylece her

bir enerji kaynağından sağlanan üretimdeki bir birimlik artışın etkilerinin ayrı ayrı değerlendirilmesine olanak tanınmıştır. Ayrıca, elektrik talebindeki bir birimlik artışın 2023 yılında gözlemlenen elektrik üretim karması kullanılarak karşılandığı ek bir senaryo da analiz edilmiştir.

Senaryoların ikinci bölümü, artan elektrik talebini karşılamak amacıyla 2023 yılı elektrik üretimini %1 artıracak farklı elektrik üretim teknolojilerine yönelik yatırımların etkilerine odaklanmaktadır. Bu kapsamda, 2023 yılı toplam elektrik üretiminin %1'ine karşılık gelen elektrik miktarının yalnızca ilgili enerji teknolojisinden üretilmesi için gerekli kurulu kapasite, ilgili kapasite faktörleri dikkate alınarak hesaplanmaktadır. Ardından, hesaplanan kurulu kapasite değerleri ilgili yatırım maliyetleri ile çarpılmaktadır. En yüksek maliyetli seçenek olan hidroelektrik enerji referans alınarak, aynı yatırım maliyetiyle diğer enerji teknolojilerinde kurulabilecek kapasiteye karşılık gelen yatırım büyüklükleri hesaplanmaktadır. Söz konusu karşılaştırmalı yatırım değerleri, SHM çarpan analizinde kullanılan temel girdileri oluşturmaktadır.

Çalışmada, jeotermal elektrik üretimine ek olarak, jeotermal ısı üretim kapasitesinin genişletilmesinin etkileri de değerlendirmektedir. Prensip olarak, jeotermal ısı ya doğrudan ısı pompaları veya toprakla bağlantılı ısı eşanjörleri aracılığıyla ya da dolaylı olarak, kojenerasyon jeotermal santrallerinde elektrik üretiminden elde edilen atık ısının kullanılmasıyla sağlanabilir. Bu çalışmadaki senaryo analizlerinde öncelikli odak noktası, atık ısının kullanımı olduğundan, Türkiye'deki jeotermal enerji santrallerinin ısı üretim potansiyelini daha iyi ortaya koyabilmek amacıyla hem uluslararası örneklerden hem de jeotermal sektöründeki Türk uzmanlarla gerçekleştirilen görüşmelerden yararlanılmıştır. Jeotermal enerji santrallerinin ısı üretme potansiyelinin yanında, yatırım odaklı analizlerde ısıtma sistemlerinin kurulumuyla ilgili maliyetler de dikkate alınmıştır. Tüm bu veriler ışığında, bu çalışmanın senaryo analizlerinde jeotermal ısı üretim potansiyelinin elektrik üretiminin 0,25, 1, 2, 5 katı olduğu, kojenerasyon santrali için ısı dağıtım maliyetinin ise geleneksel bir jeotermal enerji santralinin maliyetinin 1,5, 2 ve 3 katı olduğu varsayılmıştır. Böylelikle, SHM'de kullanılacak nihai girdiler belirlenmiş ve çarpan analizi gerçekleştirilmiştir.

Her iki senaryo grubu analizinden de elde edilen en genel çıkarımlar ışığında; dışsal bir emtia talebi şoku senaryosunun işaret ettiği üzere, elektrik sektörünün diğer sektörlerle sahip olduğu güçlü bağlantılar ve sinerjiler sayesinde ekonomide en önemli ekonomik etkileri yaratan temel sektörlerden biri olduğu görülmektedir. Bu etkinin özellikle yenilenebilir elektrik sektöründe daha belirgin olması, yenilenebilir enerji kapasitesindeki artışın ekonomik büyümeyi destekleyici rolünü açık biçimde ortaya koymaktadır. Ayrıca, fosil enerji kaynaklarının genel ekonomi üzerindeki görece sınırlı katkısı, yenilenebilir enerji gelişimine dayalı bir büyüme stratejisinin, fosil enerji kaynaklarına bağımlılığın sürdürülmesine kıyasla daha yüksek ekonomik kazanımlar sağlayabileceğini doğrulamaktadır.

Elektrik sektörü yatırım senaryolarından elde edilen kanıtlar, jeotermal enerjinin, elektrik üretimiyle sınırlı kaldığında, diğer enerji kaynaklarına kıyasla nispeten daha düşük ekonomik etkilere sahip olduğunu göstermektedir. Bununla birlikte, jeotermal enerji santrali yatırımları ısı üretimini de içerdiğinde, jeotermal enerji bu açığı kapatabilmekte ve bazı durumlarda, azalan yatırım maliyetleri ve artan ısı üretim potansiyeli sayesinde alternatif teknolojileri geride bırakabilmektedir. Böylelikle, jeotermal enerji fosil yakıtlara bağımlılığın ve karbon emisyonlarının azaltılmasına katkı sağlarken, enerji arz güvenliğini güçlendirerek ekonomik büyümeyi desteklemektedir.

Bu çalışmanın bulguları, jeotermal enerji yatırımlarının, sektörün ekonomik potansiyelinden tam anlamıyla yararlanılabilmesi için doğrudan kullanım amaçlı ısı üretimini de içerecek şekilde planlanması gerektiğini göstermektedir. Bu kapsamda, mevcut jeotermal santrallerde atık ısı kullanımını teşvik eden mekanizmaların geliştirilmesi veya yeni projelerde kojenerasyon uygulamalarının ruhsatlandırma ve izin süreçlerinin bir parçası haline getirilmesi, hem kaynak verimliliğini artıracak hem de Türkiye'nin jeotermal potansiyelinin daha etkin kullanılmasını sağlayacaktır. Bunun yanı sıra, Türkiye'nin elektrik üretiminde uyguladığı teşvik mekanizmaları sayesinde jeotermal yatırımlarda kayda değer bir büyüme sağlamış olması, benzer desteklerin ısı üretimi için de tasarlanabileceğini göstermektedir. Bu noktada, ısı üretimine yönelik ulusal fiyat temelli destek programları ve altyapı teşvikleri, proje geliştiricileri açısından uzun vadeli gelir güvencesi sağlayarak jeotermal ısıtma uygulamalarının yaygınlaşmasını destekleyecektir.

6. HESAPLANABİLİR GENEL DENGE MODELİ İLE TÜRKİYE'DE JEOTERMAL ENERJİ GELİŞİMİNİN ANALİZİ

Bu bölüm, çalışma kapsamında MPSGE (Mathematical Programming System for General Equilibrium) çerçevesi kullanılarak geliştirilen Hesaplanabilir Genel Denge (HGD) modelinin yapısal ve matematiksel çerçevesini sunmaktadır. İlk olarak, temel modelin MPSGE'ye eşdeğer bir versiyonu, cebirsel HGD modeli (GeoCGE-TR) oluşturulmuştur. Ardından, uygun iç içe geçmiş (nesting) yapıların ve özellikle jeotermal enerjiye odaklanan alternatif senaryoların modele entegre edilmesiyle model genişletilmiş ve GeoMPSGE-TR olarak geliştirilmiştir.

Genel denge teorisi, ekonomiyi kendi çıkarları doğrultusunda arz ve talep kararları alan ekonomik aktörlerin birbirine bağlı bir sistemi olarak kavramsallaştırmaktadır (Bryant, 2010). Üreticiler karlarını, tüketiciler ise faydalarını maksimize ettiğinde, bu kararların etkileşimi, tüm mal ve faktör piyasalarında talep ve arz miktarlarının eşit olduğu ekonomi genelinde bir dengeye yol açmaktadır (Blaug, 1992). Bu şekilde, genel denge modelinin çözümü, aynı anda arz ve talep miktarını karşılayan bir mal ve faktör fiyatları vektöründen oluşmaktadır (Çırpıcı, 2008). Mikroekonomik temellere dayanan genel denge modelleri, farklı piyasalar ve sektörler arasındaki ilişkilerin yanı sıra ekonomik aktörlerin davranışlarına odaklanmaktadır (Karadag, 1997).

Genel denge kuramının temelleri 1874'te Leon Walras tarafından atılmış olsa da, HGD modellemesi, Arrow ve Debreu'nun (1954) Walrasçı genel dengenin varlığını resmen kanıtlaması ve Johansen'in (1960) ilk çok sektörlü büyüme modeliyle ortaya çıkmıştır. Johansen'in çalışmalarına dayanarak, Scarf (1967), Arrow-Debreu tipi ekonomik modeller için bir algoritma geliştirerek HGD modellemesine önemli bir katkı sağlamıştır.

Genel denge modellerinde "hesaplanabilir" kavramı, ekonomiye uygulanan bir politika değişikliği veya dışsal şokun ekonomi genelindeki etkilerinin sayısal olarak ölçülebilmesini ifade etmektedir. "Genel" kavramı, ekonomideki tüm üretim, tüketim ve ticaret faaliyetlerinin birbirleriyle etkileşim içinde eş zamanlı olarak temsil

edilmesini vurgularken; “denge” kavramı ise tüm piyasalarda arz ve talebin belirli bir fiyatlar kümesi altında aynı anda eşitlendiği durumu ifade etmektedir (Burfisher, 2011). Bu çerçevede, uygulamalı genel denge modelleri, Walrasçı genel denge teorisinin soyut yapısını gerçek ekonomilerin kurumsal ve sektörel özelliklerini yansıtan ampirik modellere dönüştürmeyi amaçlamaktadır (Shoven ve Whalley, 1984, s. 1007). Teorik genel denge analizleri ağırlıklı olarak denge varlığının, tekliğinin ve istikrarının matematiksel olarak kanıtlanmasına odaklanırken, HGD modelleri politika değişiklikleri, dışsal şoklar veya yapısal dönüşümlerin ekonomi üzerindeki etkilerini nicel olarak analiz etmeyi amaçlamaktadır.

HGD modellerinin SHM tabanlı yaklaşımlara göre en önemli üstünlüğü, ekonomik aktörlerin davranışlarını ve piyasa etkileşimlerini açık biçimde modelleyebilmesidir. SHM, ekonomideki gelir ve harcama akımlarını gösteren statik bir muhasebe çerçevesi sunarken, HGD modelleri bu yapıyı davranışsal denklemlerle genişleterek üretim, tüketim ve kaynak tahsisi süreçlerini modele dâhil etmektedir (Buehrer ve di Mauro, 1993). Ayrıca, SHM çarpan analizleri sabit fiyat varsayımı altında ağırlıklı olarak geriye dönük bağlantıları incelerken, HGD modelleri fiyat ayarlamaları ve genel denge mekanizması sayesinde ekonomik şokların doğrudan ve dolaylı etkilerini eş zamanlı olarak analiz edebilmektedir (Alkan, 2018). Bu özellikleri sayesinde HGD modelleri, politika değişikliklerinin sektörel, makroekonomik ve refah etkilerinin daha gerçekçi ve tutarlı biçimde değerlendirilmesine olanak sağlamaktadır (Mukherjee, 1995; Ghaith vd., 2021).

HGD modelleri, statik veya dinamik çerçevede kurulabilmektedir. Statik HGD modelleri, ekonominin belirli bir dönemde başlangıç dengesinden yeni dengeye uyumunu karşılaştırmalı statik analiz yoluyla incelerken, dinamik HGD modelleri zaman boyutunu dikkate alarak politika etkilerinin birden fazla dönem boyunca nasıl geliştiğini analiz etmektedir (Iqbal ve Siddiqui, 2001). Statik modeller yalnızca başlangıç ve yeni denge arasındaki farkı değerlendirirken, dinamik modeller sermaye birikimi ve ekonomik büyüme gibi zaman içinde değişen süreçleri de kapsar (Narayan ve Prasad, 2007; Şenerdem, 2016). Ayrıca, tam dinamik modellerin karmaşıklığını azaltmak amacıyla, önceki dönem sonuçlarının sonraki dönem parametrelerini güncellediği özyinelemeli (recursive) dinamik HGD modelleri de yaygın olarak kullanılmaktadır (Thurlow, 2008).

HGD modelinin geliştirilmesi, ekonomik teori ve analiz edilen politika senaryosuyla tutarlı, uygun bir model tasarımına karar verilmesiyle başlamaktadır (Böhringer vd. 2003). Teorik çerçeve oluşturulduktan sonra, HGD modellemesi, veri kümesinin oluşturulması, fonksiyonel formların belirlenmesi, kalibrasyon ve politika simülasyonu dahil olmak üzere bir dizi standart hesaplama adımıyla ilerlemektedir.

HGD modellerinde hanehalkları gelir ve tüketim kararlarını, firmalar ise üretim ve girdi kullanımını tanımlayan davranışsal denklemlerle temsil edilmektedir (Ghaith vd., 2021). SHM'nin oluşturulmasının ardından model, üretim teknolojileri ve tüketici tercihlerini yansıtan uygun fonksiyonel yapılarla formüle edilir. Bu amaçla, genel denge koşullarını sağlayan ve Walras Yasası ile uyumlu Sabit İkame Esnekliği (CES) fonksiyonları ile bunların özel durumları olan Cobb-Douglas ve Leontief fonksiyonları yaygın olarak kullanılmaktadır (Annabi vd., 2006; Karadağ, 1997). Politika analizlerinde ise modelde belirli parametreler veya dışsal değişkenler değiştirilerek yeni bir karşı olgusal denge (counterfactual equilibrium) elde edilir. Bu denge, referans denge ile karşılaştırılarak politika değişikliklerinin üretim, tüketim, istihdam, gelir ve fiyatlar üzerindeki etkileri değerlendirilmektedir (Böhringer vd., 2003).

Literatürde jeotermal enerjiye odaklanan HGD çalışmalarının sayısı, diğer yenilenebilir enerji teknolojilerine kıyasla oldukça sınırlıdır. Mevcut çalışmalar, jeotermal enerjinin ekonomik büyümeyi destekleme, sera gazı emisyonlarını azaltma, elektrik fiyatlarını düşürme ve enerji arz güvenliğini artırma potansiyeline odaklanmakta; çoğunlukla enerji yatırımları, karbon vergileri, sübvansiyon reformları ve gelir geri dönüşüm mekanizmalarını içeren politika senaryolarını analiz etmektedir. Ancak bu çalışmaların büyük bölümü belirli ülke örnekleriyle sınırlı olup, özellikle Türkiye gibi yüksek jeotermal potansiyele sahip ülkelerde jeotermal enerjinin makroekonomik, sektörel ve çevresel etkilerini inceleyen HGD analizleri oldukça yetersizdir. Bu nedenle, elektrik sektörünü ayrıntılı biçimde temsil eden ve jeotermal elektrik ile jeotermal ısı üretimini ayrı sektörler olarak modelleyen bir HGD modelinin geliştirilmesi, Türkiye literatürüne önemli katkılar sağlayacaktır.

Türkiye üzerine yapılan enerji HGD çalışmaları incelendiğinde, jeotermal enerjinin çoğu zaman diğer enerji kaynakları içerisinde değerlendirildiği, bağımsız bir elektrik

üretim teknolojisi olarak ayrıştırılmadığı görülmektedir. Ayrıca, mevcut literatürde jeotermal enerjiye dayalı politika senaryolarını açık biçimde analiz eden bir HGD çalışmasına rastlanmamaktadır. Bu yönüyle çalışma, jeotermal enerjiyi Türkiye için geliştirilen bir HGD çerçevesine açık biçimde entegre eden öncü çalışmalardan biri olma niteliği taşımaktadır. Ayrıca, jeotermal elektrik üretiminin yanı sıra jeotermal ısı kullanımını da modele entegre ederek çalışma, jeotermal enerjiye ilişkin mevcut HGD literatürünü genişletmeyi ve bu enerji kaynağının daha kapsamlı bir şekilde temsil edilmesini mümkün kılmayı amaçlamaktadır. Literatürdeki bu boşluğu doldurmanın yanı sıra, mülakat yapılan paydaşlar tarafından önemi sıklıkla vurgulanan teşvik mekanizmalarına ilişkin senaryolardan elde edilen bulgular, jeotermal elektrik kurulu gücünün artırılmasında ve Türkiye'nin uzun vadeli jeotermal elektrik üretim hedeflerine ulaşılmasında teşviklerin rolüne ilişkin politika yapıcılara önemli çıkarımlar sunmaktadır.

HGD modellerinin formülasyonunda, açık cebirsel gösterimlerin yanı sıra, Rutherford (1994) tarafından GAMS için geliştirilen MPSGE (Mathematical Programming System for General Equilibrium), kompakt ve tablo temelli bir modelleme alternatifi sunmaktadır. MPSGE, karmaşık HGD modellerinin oluşturulmasını kolaylaştırarak teknoloji, faktör donanımları, tercihler ve vergi oranları gibi girdilerden arz ve talep fonksiyonlarını otomatik olarak türetmektedir (Cretegny vd., 2004; Pradhan vd., 2023). Referans miktarlar, referans fiyatlar ve ikame esneklikleri kullanılarak temel üretim ve fayda fonksiyonları oluşturulabilmekte (Paltsev, 2004); ayrıca iç içe geçmiş CES fonksiyonlarını doğal olarak desteklemesi sayesinde karmaşık üretim ve tüketim yapılarının modellenmesi ile alternatif politika senaryolarının analiz edilmesi önemli ölçüde kolaylaşmaktadır (Rutherford, 1999).

Çalışma kapsamında ilk olarak cebirsel HGD modeli (GeoCGE-TR) GAMS kullanılarak oluşturulmuş, daha sonra referans denge çözümü ile modelin dayandığı teorik çerçevenin içsel tutarlılığını test etmek amacıyla kalibre edilmiştir. Ancak, elektrik sektörünün cebirsel çerçeve içerisinde temsil edilmesine ilişkin bazı kısıtlar nedeniyle analizler modelin MPSGE'ye eşdeğer versiyonu üzerinden yürütülmüştür. Bu doğrultuda model, elektrik sektöründeki çok katmanlı üretim yapılarının ve ikame

ilişkilerinin daha esnek ve içsel olarak tutarlı bir şekilde temsil edilebilmesi amacıyla MPSGE çerçevesinde yeniden formüle edilmiştir.

Modelin temel güçlü yönlerinden biri, elektrik ve buhar sektörlerini ayrıntılı bir yapıda temsil etmesidir. Elektrik üretimi tek bir faaliyet olarak ele alınmak yerine altı farklı üretim teknolojisine ayrıştırılarak kesintili, sevk edilebilir ve baz yük özelliklerine sahip teknolojiler birbirinden ayrılmıştır. Bu sayede teknoloji payı hedefleri, teşvik politikaları ve üretim faktörlerinin sektörler arası yeniden tahsisine ilişkin politika senaryolarının ekonomi genelindeki etkileri ayrıntılı olarak analiz edilebilmektedir.

Çalışmada, üretim, tüketim, yatırım ve refah gibi temel bloklardan oluşan GeoMPSGE-TR modeli, 23 ana sektör temelinde oluşturulmuş; elektrik ve ısı sektörleri ise daha ayrıntılı analizlere olanak sağlamak amacıyla farklı alt sektörel kırılımlar şeklinde modellenmiştir. Ayrıca GeoMPSGE-TR modeli, 2023-2035 dönemini kapsayan özyinelemeli dinamik (recursive dynamic) bir yapıda geliştirilmiş olup, 2023 denge çözümü 2035 döneminin başlangıç koşullarını oluşturmakta olup böylece sermaye birikimi, yatırım ve diğer zaman içinde değişen ekonomik değişkenler dönemler arasında güncellenerek ekonominin zaman içindeki uyum süreci analiz edilebilmektedir. Söz konusu model çok çeşitli alternatif senaryoların analiz edilmesine olanak tanımakla birlikte, bu çalışma özellikle politika teşvikleri (sübvansiyonlar) ile jeotermal elektrik kapasitesi genişlemesi arasındaki ilişkiye odaklanmıştır. Bu kapsamda, jeotermal enerjinin gelişiminin politika desteğine ne ölçüde bağlı olduğunun ortaya konulması amaçlanmıştır.

Çalışma sonunda elde edilen bulgular, Türkiye'de jeotermal sektörünün büyümesinde teşviklerin kritik bir rol oynadığını ve gelecekteki kapasite artışları için istikrarlı ve uzun vadeli destek politikalarının gerekli olduğunu ortaya koymaktadır. Sonuçlar ayrıca, jeotermal enerjinin fosil yakıt bazlı elektrik üretimini ikame ederek hem karbonsuzlaşma hem de enerji arz güvenliği ve ekonomik büyüme hedeflerine katkı sağlayabileceğini göstermektedir. Bununla birlikte, jeotermal elektrik kapasitesinin yüksek teşvik seviyelerinde dahi doğal bir genişleme sınırına yaklaştığı görülmektedir. Bu nedenle, gelecekteki politikalar yalnızca elektrik üretimine değil,

Türkiye'nin önemli potansiyele sahip olduğu doğrudan kullanım uygulamalarına da odaklanmalıdır. Böylece jeotermal kaynakların daha verimli değerlendirilmesi sağlanarak ekonomik ve sosyal faydalar artırılabilecektir.

7. SONUÇ VE ÖNERİLER

Diğer birçok yenilenebilir enerji kaynağından farklı olarak jeotermal enerji, elektrik üretiminin yanı sıra geniş bir doğrudan kullanım potansiyeline sahiptir. Ancak Türkiye'de uygulanan politika teşvikleri ağırlıklı olarak elektrik üretimine odaklanmış; bu sayede elektrik kurulu gücü hızla artmış ve özel sektör yatırımları teşvik edilmiştir. Buna karşın, doğrudan kullanım uygulamaları sınırlı kalmış, elektrik kapasitesindeki hızlı ve kontrolsüz büyüme süreci kurumsal, sosyal ve çevresel bazı sorunları da beraberinde getirmiştir. Bu nedenle, Türkiye'de jeotermal enerjinin sürdürülebilir gelişimi için elektrik üretimi ile doğrudan kullanım uygulamalarını birlikte ele alan daha dengeli bir yaklaşım gerekmektedir.

Tez bulguları, jeotermal enerjinin potansiyelinin tam olarak değerlendirilebilmesi için mikro, mezo, makro ve uluslararası düzeyleri kapsayan bütüncül bir politika çerçevesine ihtiyaç olduğunu göstermektedir. Mikro düzeyde yatırım risklerini azaltan finansman mekanizmaları ve teknoloji geliştirme destekleri; mezo düzeyde Ar-Ge, yerli üretim ve sektör paydaşları arasındaki iş birliğinin güçlendirilmesi; makro düzeyde jeotermal enerjinin ulusal enerji politikalarına daha güçlü biçimde entegre edilmesi, teşvik mekanizmalarının geliştirilmesi, doğrudan kullanım uygulamalarının desteklenmesi, çevresel sürdürülebilirliğin sağlanması ve sosyal kabulün arttırılması öncelikli politika alanları olarak öne çıkmaktadır. Uluslararası düzeyde ise finansman, teknoloji transferi ve araştırma iş birliklerinin artırılması önem taşımaktadır.

Sonuç olarak, Türkiye deneyimi, jeotermal enerjide kurulu gücün artırılmasının tek başına sürdürülebilir sektör gelişimini sağlamaya yeterli olmadığını ortaya koymaktadır. Sektörün uzun vadeli gelişimi; yatırım, inovasyon, yönetişim, çevresel sürdürülebilirlik, sosyal kabul ve uluslararası iş birliğini bütüncül biçimde ele alan, elektrik üretiminin yanı sıra jeotermal kaynağın doğrudan kullanım uygulamalarını da destekleyen çok düzeyli bir politika yaklaşımını gerektirmektedir.

Bu araştırma, Türkiye'de jeotermal enerji gelişimini TİS, SHM ve HGD yaklaşımlarını bütüncül bir çerçevede kullanarak incelemiş ve böylece ilgili literatüre kurumsal, politika ve sosyo-ekonomik boyutları bir araya getiren özgün katkılar sunmuştur. Türkiye'de jeotermal enerji çalışmalarının ağırlıklı olarak mühendislik ve teknoloji odaklı olması nedeniyle, bu tez jeotermal enerjiyi yalnızca teknik bir konu olarak değil, aynı zamanda politika, yönetişim ve ekonomik dinamiklerle şekillenen çok boyutlu bir süreç olarak ele almış; ayrıca politika yapıcılar için karar alma süreçlerini destekleyecek bulgular ortaya koymuştur.

Bununla birlikte, çalışmanın bazı sınırlılıkları bulunmaktadır. Jeotermal enerjinin sosyal ve çevresel etkileri doğrudan nicel yöntemlerle analiz edilmemiş olup, bu boyutlar gelecekte çevresel göstergeleri içeren gelişmiş SHM ve HGD modelleri ile saha araştırmaları kullanılarak daha ayrıntılı incelenebilir. Ayrıca, Türkiye'de kapsamlı bir jeotermal veri tabanının oluşturulması, uzun dönemli zaman serisi ve bölgesel karşılaştırmalı analizlerin yapılmasına olanak sağlayabilir. Son olarak, farklı ülkelerin deneyimlerini kapsayan daha kapsamlı uluslararası karşılaştırmalar, jeotermal enerji politikalarının ve gelişim süreçlerinin daha derinlemesine değerlendirilmesine katkı sağlayabilir.

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