“Novel Drilling Technology Combining Hydro-Jet and Percussion for ROP Improvement in deep geothermal drilling”

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DELIVERABLE D3.3

“Report on energy security”

ABSTRACT

This report on Energy Security (D3.3) evaluates the impact of geothermal energy development on the energy security of 35 countries Following a literature review, a custom quantitative index of energy security was formulated, selecting seven dimensions and 33 indicators. The energy security index was calculated by aggregating the corresponding dimensional subindexes: physical availability, technology development (including the role of geothermal energy), economic affordability, social accessibility, governance, manmade threats, and natural environment. The indicator values, collected from various sources for a baseline year of 2020, are standardized and averaged with weights assigned to each dimension by an ad-hoc energy expert panel. Energy security values are calculated, and the countries are ranked in descending order of their energy security index. Scandinavian countries and the US received high rankings while Turkey, India, and Bulgaria received low rankings in their energy security index. Changes in the level of energy security were also evaluated for three future scenarios targeting the years 2030 and 2050. A smaller subset of indicators with available historical data were forecast using appropriate time series methods, and a more concise version of the energy security index was calculated for selected countries and regions with available data. The energy security index of some countries was found to improve or worsen, causing their position in the ranking to change.

The findings suggest that some countries in Europe could meet all of their electricity needs through geothermal energy, while others could have a significant share of geothermal in their energy mix. By analyzing the technical and sustainable geothermal potential in the literature, the report emphasizes the potential role of enhanced geothermal drilling techniques such as ORCHYD, which can help countries access currently underutilized or inaccessible geothermal resources and improve their energy security.

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Executive summary

This deliverable (D3.3) extends the scope of previous tasks by examining ORCHYD's impact on energy security.

The deliverable commenced with a literature review that showed that the concept of energy security has emerged as a critical issue in the twenty-first century. This growing interest may be explained by several factors, including: increased energy prices; the growing dependence of industrialized economies on energy as an engine for economic growth; climate change; energy demand and competition; political conflict; significant disruptions in oil markets, and a complex global market.

Energy security may be generally defined as the uninterrupted availability of energy sources at an affordable price. Nevertheless, the definition of energy security is dynamic and constantly evolving, changing over time in response to shifting circumstances and emerging challenges. Energy security may be measured via dimensions, components, and indicators. To assess the level of energy security, an index may be calculated based on specific metrics, which are often grouped into dimensions.

To account for the impact of geothermal energy on energy security, a custom energy security index was formulated, containing the following seven dimensions and corresponding components:

1. *Physical availability:* Total energy production, oil reserves, electricity generated from fossil fuels, renewable energy generation, electricity exports, and net electricity generation.
2. *Technology development:* Global innovation index, gross domestic expenditures on research and development, energy transition index, share of energy from RES, geothermal share, installed electricity generation capacity.
3. *Economic affordability:* GDP per capita, energy intensity, and average price of one KW/h.
4. *Social accessibility:* GDP per capita, energy intensity, average price of one KWh, energy equity, global democracy index, GINI income inequality index, and electricity imports.
5. *Governance:* political stability index, military spending, and corruption perception index
6. *Manmade threats:* security threats, external intervention index, fragile state index, global cybersecurity index, and percentage of coastline.
7. *Natural environment:* Carbon dioxide emissions per capita, carbon intensity of electricity, agricultural land, forest land, and environmental sustainability index.

The decision on the number and nature of dimensions and the selection of appropriate indicators was based on the literature review carried out herein, previous research of UPRC on this topic, and data availability.

A sample of 35 countries was examined, including Austria, Belgium, Bulgaria, China, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, India, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Norway, Poland, Portugal, Romania, Russia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, and the USA.

Data for a total of 33 indicators for the year 2020 were collected from a variety of open and free sources, including the US Energy Information Administration (EIA), the World Factbook (CIA

Factbook), the British Petroleum (BP Annual Statistical Review), the World Intellectual Property Organization (WIPO), the World Economic Forum (WEF), the World Bank, the Enerdata (World Energy & Climate Statistics), the World Energy Council (WEC), the Economist, the Our World in Database, Transparency International, and the ITUPublications. These open and free data were complemented with some purchased from the Global Economy website.

The calculation process included normalizing the indicators, aggregating subindexes for each dimension, and combining them with appropriate weights derived from an ad-hoc group of experts. A final energy security index was calculated from the seven subindexes representing the aforementioned dimensions of energy security.

Countries were ranked in descending order of their energy security index for the base year of 2020. Countries such as Norway, Sweden, the US, Iceland, and Finland ranked high in the index, exhibiting strong performance across most energy security dimensions: high electricity generation capacity; a significant share of renewable energy sources in their energy mix; a high GDP per capita; low energy intensity and electricity prices; stable political systems; democratic governance; low carbon emissions; and minimal manmade threats. In contrast, Russia, Cyprus, Turkey, India, and Bulgaria had the lowest energy security rankings due to their weak performance across these subindexes.

Next, the deliverable focused on the technical and sustainable geothermal potential and its role in the energy security index. Geothermal reserves estimation is similar to the oil and gas industry, and technological advancements can expand reserves. Utilizing a fraction of global geothermal potential could provide consistent power for thousands of years, with projections of 70 GW capacity and 8.3% contribution to global electricity generation by 2050, generating 800-1300 TWh/yr of electricity and 3300-3800 TWh/yr of heat globally. In Europe, geothermal energy may account for 4-7% of electricity generation, with projected economically viable potential of 19 GW in 2020, 22 GW in 2030, and 522 GW in 2050. The research literature on geothermal potential predominantly focuses on estimating the geothermal potential for electricity generation, providing detailed data for each country, with no relevant data existing for the heat potential. It is suggested that geothermal energy can be economically exploitable for electricity production down to 7 km by 2030 and down to 10 km by 2050.

Technological improvement in the sector of Geothermal Energy is expected to reduce the costs of electricity production. The analysis carried out herein focuses on the effect of geothermal energy on electricity generation projections based on optimal drilling depths and cost assumptions for 2030 and 2050. An assessment of the economic potential for each country in 2030 and 2050 was provided, assuming that the Levelized Cost of Electricity (LCoE) will be below 150 EUR/MWh for 2030 and below 100 EUR/MWh for 2050. Considering the variation in financial support for geothermal energy across countries, the economic geothermal potential is presented as stacked potential for depths up to 7 km by 2030 and 10 km by 2050.

Six scenarios were developed, referring to the years 2030 and 2050. For the 2020-2030 decade, Scenario 2030_A took a pessimistic view, with a 42% renewable energy share in the electricity production mix and a 1.8% annual growth rate for renewable energy. Scenario 2030_B presented an intermediate perspective, with a 50% RES share and a 4% growth rate. Scenario 2030_C offered an optimistic outlook, considering the implications of the Russian invasion of Ukraine, with a 60% RES share and a 6.5% growth rate. Turning to the 2020-2050 period, Scenario 2050_A was pessimistic, with a 65% RES share and a 2.7% growth rate. Scenario 2050_B took an intermediate view, with an 80% RES share and a 4% growth rate. Lastly, Scenario 2050_C embodied an optimistic perspective in line with the EU's long-term strategy, assuming a 100% renewable energy share, a 5.1% growth rate, and the termination of natural gas and nuclear energy.

Furthermore, energy security projections to 2030 were analyzed for a reduced set of countries using an energy security index that incorporated fewer dimensions and indicators due to data availability limitations. These indicators included: electricity generation; the share of renewable and geothermal energy in electricity consumption; coastline length (as a surrogate of security threats related to borders and geography); oil reserves; electricity exports; GDP per capita; military spending; carbon dioxide emissions per capita; and the share of agricultural land. Appropriate time series techniques were used to develop projections for the energy security index up to 2030, considering three scenarios (2030_A, 2030_B, and 2030_C), and recalculating energy security rankings for the reduced set of countries.

The results showed that advancements in geothermal drilling technology, particularly the pursuit of target depths of 7-10 km as part of the ORCHYD project, could have a significant impact on the rankings. Countries such as France, Spain, Sweden, Greece, Switzerland, Italy, the UK, and the Netherlands are projected to improve their positions. The development of geothermal energy, coupled with improved grid interconnectivity, has the potential of enhancing energy security and promoting surplus electricity production in Iceland, Greece, Cyprus, Austria, Hungary, Romania, Bulgaria, and Turkey, leading to economic benefits and strengthened energy security throughout Europe.

The report was rounded up with conclusions and recommendations, highlighting the fact that the technical advances pursued by ORCHYD could contribute to a significant proportion of electricity consumption in Europe being provided by geothermal energy, enhancing the energy security of states.

1. Introduction and scope

Task 3.3 extends the scope of the previous tasks (Tasks 3.1 and 3.2: Environmental and social impact assessments) by considering the project's impact on the energy security of European and other states. In this deliverable, following an extensive literature review, a custom-made quantitative index of energy security is formulated, selecting appropriate dimensions, components, and metrics to accurately reflect the role of geothermal energy and deep geothermal drilling. As will be explained, a starting list of such dimensions includes physical availability, technology development, economic affordability, social accessibility, governance, unconventional threats, and the natural environment. These dimensions are broken down into components, with appropriate quantitative (or qualitative) indicators used as metrics.

The energy security index is formulated to incorporate the effect of salient characteristics of the deep drilling technologies developed in this project. The values of energy security are calculated so that conventional drilling is compared to the improved deep geothermal drilling technologies (with associated cost reductions) developed in the ORCHYD project. Such energy security calculations and comparisons are made at a regional and country level. Finally, the increase or decrease of the level of energy security is evaluated for a few alternative future scenarios of exploitation of deep geothermal energy.

This report is organized as follows: Section 2 describes the screening of energy security literature; Section 3 presents the methodology used to create the energy security index; Section 4 contains survey analyses and results; Finally, Section 5 summarizes the report and concludes with recommendations.

2. Review of energy security literature

2.1. Introduction

Energy security is critical to human security and has become a popular concept among policymakers, entrepreneurs, and academics (Sovacool & Mukherjee, 2011). It has emerged as a critical issue in the twenty-first century (Yergin, 2006). This growing interest can be explained by several factors, including increased energy prices (Vivoda, 2010); the growing dependence of industrialized economies on energy as an engine for economic growth (Bielecki, 2002; Le & Nguyen, 2019); climate change (Toke & Vezirgiannidou, 2013; Kim, 2014; Cevik, 2022); energy demand and competition (Vivoda, 2010); political conflict (Jonsson et al., 2015; Nance & Boettcher, 2017); significant disruptions in oil markets (Löschel, Moslener, & Rübbelke, 2010; Hedenus, Azar, & Johansson, 2010), and complex global market (Chester, 2010).

2.2. Defining energy security

Sovacool (2013) considers energy security as a complicated, multifaceted, and dynamic concept. Yergin (2006) argued that energy security lacks a clear and precise definition, and thus there is no universally accepted concept of energy security (Ang, Choong, & Ng, 2015a; Augutis et al., 2020). However, energy security is a matter of national security for many developed countries (Månsson et al., 2014). Energy security can have varying definitions and priorities due to differences in natural resources, political systems, economic well-being, ideologies, geographical locations, and international relations among countries (Luft & Korin, 2009; Chester, 2010; Winzer, 2012). As a result, it is not unexpected to find a multitude of definitions for energy security (Winzer, 2012).

A wide range of definitions of energy security exist in the literature (Sovacool & Mukherjee, 2011). According to Sovacool (2011), until 2011 there were at least 45 comparable definitions of energy security, causing challenges in terms of the practical application of the concept. Ang, Choong and Ng (2015a) identified 83 energy security definitions in the literature. As pointed out by Cherp and Jewell (2014), a classic definition of energy security is provided by Yergin (1988), who visualized energy security as the assurance of *"adequate, reliable supplies of energy at reasonable prices,"* adding a geopolitical component by qualifying that this assurance must be provided *"in ways that do not jeopardize national values or objectives."* Yergin's definition identifies *"national values and objectives"* as the assets to safeguard energy security.

Chester (2010) and Vivoda (2010) highlight the polysemic and multi-dimensional nature of energy security. Chester suggested that the prominence of the term energy security in government policy discussions is due to the intricate system of global markets, extensive cross-border infrastructure networks, and the limited number of primary energy providers. Månsson, Johansson, and Nilsson (2014) have described energy security as a dynamic concept, with a perspective that depends on the time frame analyzed. As challenges in energy policy have arisen, the attempts to define energy security have evolved over the years (Winzer, 2012; Song, Zhang, & Sun, 2019).

Countries may define energy security differently depending on their special circumstances, level of economic development, risk perceptions, robustness of their energy system, and current geopolitical issues (Ang, Choong, & Ng, 2015a). Countries differ not only in their definition of energy security but also in how they address energy security challenges, according to Luft and Korin (2009). This differentiation is based on their geographical location, their natural resource endowment, the status of their international relations, their political system, and their economic disposition. At the same time it is based on their ideological views and perceptions (Marquina, 2008).

According to Martišauskas, Augutis, and Krikštolaitis (2018), some of the most prevalent concepts encompassed by the definitions of energy security include *"reliable and uninterrupted supply"*, *"reasonable or affordable price"*, *"energy availability"*, and *"diversity"*. On the other hand, fundamental concepts such as threat, risk, disruption, robustness, vulnerability, and resilience are often overlooked in the definition, conceptualization, or evaluation of energy security.

Given the absence of a clear definition (Kruyt et al., 2009; Chester, 2010), energy security has become an umbrella term encompassing various policy objectives (Winzer, 2012). The diversity of definitions is shaped by the perspective and circumstances of different countries, as well as their position in the energy chain and the intricate global energy system. Consequently, the concept has become diffuse and often inconsistent (Sovacool & Mukherjee, 2011).

In his study, Chester (2010) accurately characterized energy security as *"slippery"* and *"polysemic"* due to the numerous concepts and dimensions involved in the domain of energy security. Energy availability is undoubtedly the primary consideration in energy security definitions (Ang, Choong, & Ng, 2015a).

The International Energy Agency (IEA), a pioneer institution in the field of energy security and a prominent multinational platform, defines energy security as the "uninterrupted availability of energy sources at an affordable price." According to the IEA, energy security encompasses both short-term and long-term aspects. Short-term energy security pertains to the ability of the energy system to promptly respond to sudden shifts in the supply-demand balance, as stated by the IEA (2011), Jewell (2011), and Kisel et al. (2016). On the other hand, long-term energy security involves making timely investments to meet energy demands in accordance with economic developments and environmental requirements, as outlined by the IEA (2011). Numerous studies, including the research conducted by Augutis et al. (2020), support the definition of energy security provided by the IEA. However, the IEA has revised its definition over the years to emphasize the importance of adequate, affordable, and reliable energy supply. In 2000, the European Commission (EC) expanded on the IEA definition and referred to energy supply security as the "uninterrupted physical availability of energy products on the market, at a price that is affordable for all consumers (private and industrial), while also taking into consideration environmental concerns and striving towards sustainable development" (EC, 2000). This extended definition incorporated environmental and sustainability aspects into the concept of energy supply security.

Energy security is a field dominated by a traditional approach to security and means different things to different countries. As a result, countries may be divided into three groups based on their energy priorities: (a) producers/exporters that wish to ensure reliable demand for their commodities; (b) consumers that commonly aim towards diversity of energy supply to maximize their security; and (c) transit states that strive to remain the essential bridges connecting producers/exporters with their markets (Luft & Korin, 2009). Both oil exporters (due to varying revenues) and oil importers (due to significant uncertainty about import costs and fuel subsidies) suffer as a result of low oil prices (Raghoo et al., 2018). Thus, countries may differ in how they address energy security challenges. The approaches to energy security may vary between countries, depending on the structure of their energy system and historical experiences.

The diversity of definitions is shaped by the perspective and nature of different countries; their place in the energy chain; their vulnerability to energy supply disruptions; their role in the complex global energy system; and the historical period. As an example, security of supply may be a more important concept for importer countries while security of demand may be an equally important concept for exporter countries (Johansson, 2013).

Newer definitions of energy security include the four main dimensions of availability, accessibility, affordability and acceptability (Kruyt et al., 2009).

2.2.1. Energy security and renewable energy

Renewable energy burst into the scene in the 1970s, but from discovery until its rebirth around the beginning of the 21st century, it went through a period of technological immaturity and economic stagnation known as the *"valley of death"* (Hartley & Medlock, 2017). Since then, it has scaled up, been commercialized, and diffused, with electric utilities now buying into mainly wind energy without hesitation.

Climate change and the energy crisis have compelled several major economies to enhance their energy efficiency efforts. In recent decades, renewable energy has grown in importance and efficiency (Chu et al., 2023). Deploying renewable energy technologies can help achieve the goal of energy security, while also providing numerous other benefits, such as reducing greenhouse gas emissions and improving public health. Renewable energy can enhance energy security by diversifying the mix of energy sources used for electricity generation. The spatial location, types of generation resources, and fuel sources or supply all contribute to the diversity of an energy mix. Renewable energy can enhance energy security by helping to maintain energy services during disruptions. Examples of disruptions to energy services include natural events such as severe weather, technological events such as cyberattacks, and human-caused events such as supply chain disruptions.

The viability and adoption of renewable energy depend on a variety of factors, including the economic costs and benefits of the technology, the availability of energy resources, and the environmental impacts of energy generation and use (Bourcet, 2020). As renewable energy development is of great importance, much of the literature has focused on the impact of economic growth and trade on the utilization of renewable energy sources (RES). The concept of energy security risk encompasses a wide range of factors, including the availability of energy reserves, the cost of energy expenditures, the volatility of energy prices, the efficiency of energy use (often referred to as energy intensity), transportation infrastructure, and environmental impacts of energy generation and use (Chu et al., 2023).

2.3. Dimensions and components of energy security

The definition and dimensions of energy security are dynamic and constantly evolving, changing over time in response to shifting circumstances and emerging challenges, according to Ang, Choong, and Ng (2015a). In a paper examining 40 years of energy security trends, Brown et al.

(2014) found that 91 peer-reviewed academic articles covered the dimensions of energy security differently. In particular, availability was covered by 82% of the examined articles; affordability by 51% of the articles; energy and economic efficiency by 34% of the articles; and environmental stewardship by 26% of the articles. The precise dimensions of energy security were analyzed through a Factor Analysis conducted by the authors. The results indicated that availability was primarily determined by oil import dependence, followed by road fuel intensity and natural gas import dependence (in decreasing order of importance). Affordability was found to be a function of retail prices for electricity and gasoline. Energy and economic efficiency were associated with electricity use per capita and energy per GDP intensity. Finally, environmental stewardship was primarily determined by CO_2 and SO_2 emissions.

The Asia Pacific Energy Research Centre (APERC, 2007) extended the IEA definition of energy security by introducing the concept of the *“four As”* of energy security. These included the availability of energy resources, the affordability of energy prices to avoid negative economic impacts, the accessibility of energy to all social actors, and the acceptability of energy from a sustainability standpoint. The first two As, availability and affordability, reflect the classic approach to energy security from the 20th century. In contrast, the latter two As, accessibility and acceptability, reflect contemporary concerns from the 21st century such as fuel poverty and global climate change. Previous work by Hughes and Shupe (2010) has validated this approach to energy security.

Building on the previous discussion of the four As of energy security, it is worth noting that some scholars (Ang, Choong, & Ng, 2015; Hossain, Loring, & Marsik, 2016) have used this framework and have explored ways to enhance it. For instance, it may be argued that different energy sources are characterized by differing importance of their dimensions, e.g., with oil, physical and economic availability may be its preeminent aspect, while with shale oil and gas, environmental acceptability may be its most important concern. Furthermore, as discussed in an upcoming section, additional dimensions of energy security may need to be considered in response to changing circumstances and new challenges. Energy security is theoretically linked to geopolitical dimensions, financial dependence, trade openness, and the level of international cooperation of its home/host country with the rest of the world (Wang et al., 2022).

Availability is a fundamental dimension of energy security and is widely included in literature definitions, referring to the physical availability and supply security of energy resources (IEA, 2007; Narula & Reddy, 2015; Ang, Choong, & Ng, 2015a). Physical security, i.e. uninterrupted supply, is so important for energy security (Luft & Korin, 2009) that is used oftentimes as a synonym for energy security (Kruyt et al., 2009), particularly by researchers adopting an economic perspective (Johansson 2013; Jansen & Seebregts 2010; Keppler, 2007; Le Coq & Paltseva, 2009). According to Ang, Choong, and Ng (2015a), diversification and geopolitical factors are key issues that determine energy availability. Energy prices are a crucial factor in determining the affordability of energy supplies. They can be measured in several dimensions, including the absolute price level, price volatility, and the degree of competition in energy markets.

Sovacool and Rafey (2011) have proposed a similar set of four dimensions of energy security. These include availability, which involves diversifying fuels, preparing for disruption recovery, and minimizing dependence on foreign supplies; affordability, which entails providing affordable energy services and minimizing price volatility; efficiency and development, which involves improving energy efficiency, altering consumer attitudes, and developing energy infrastructure; and environmental and social stewardship, which involves protecting the natural environment, communities, and future generations.

Some definitions of energy security (IEA, 2007; EC, 2000; Yergin, 2006) also use the term availability to imply a stable and uninterrupted supply of energy, while others (Jun, Kim & Chang, 2009; WEC, 2016a) use the term reliability to refer to the role of energy infrastructure. Infrastructure is considered to help provide a stable and uninterrupted energy supply (Ang, Choong, & Ng, 2015a). According to Vivoda (2010), numerous studies in the literature focus primarily on the reliability of oil supply for two reasons: first, oil is the most consumed primary energy resource in the world, and second, oil prices often fluctuate as a result of political instability and conflicts in major oil producing countries (Asif & Muneer, 2007).

As for accessibility, it has been at the center of energy security debates and policy approaches into the 21st century (Kopp 2014). Cherp and Jewell (2014) compared the four As to the five As of access to health care (availability, accessibility, accommodation, affordability and acceptability).

In a paper surveying the attitudes of energy consumers towards energy security, Knox-Hayes et al. (2013) extracted the following dimensions of energy security: (1) availability, indicating both security of supply and affordability; (2) welfare, indicating equity and environmental quality; (3) efficiency, representing various factors including low energy intensity and small-scale energy (with some equity overlap with welfare); (4) affordability, indicating (among other factors) price affordability and small-scale energy; (5) environment, appearing to be very similar to welfare; (6) transparency, standing for equity, transparency and education; (7) climate, connected to global climate change and having significant overlap with welfare and environment; and (8) equity, overlapping with other dimensions covering equity. These dimensions were characterized by significant overlap.

In a work examining the role of coal in energy security, Sovacool, Cooper, and Parenteau (2011) considered the following four criteria, which correspond to dimensions of energy security: (1) availability, i.e. fuel diversification and reduced dependence on foreign supplies; (2) affordability, i.e. affordable energy services and reduced price volatility; (3) efficiency, i.e. innovation, performance of energy equipment, and consumer behavior; and (4) stewardship, i.e. social and environmental sustainability.

In a paper assessing five different energy security policy packages, Sovacool and Saunders (2014) discussed the complexity of energy security by citing Drexel Kleber, the Director of the Strategic Operations Power Surety Task Force of the US Department of Defense, who argued that energy security is an amalgamation of the following five Ss: (1) surety, i.e. certainty of access to energy and fuel sources; (2) survivability, i.e. resilience and durability against potential damage; (3) supply, i.e. physical availability of energy resources; (4) sufficiency, i.e. adequacy of supply from various sources; and (5) sustainability, i.e. prolongation of supply with mitigation of environmental impacts. The authors conceptualized energy security as having the following dimensions: (1) availability of energy fuels and services, which they call the bedrock of energy security; (2) affordability, i.e. stable and affordable costs for current and future generations (encompassing a sense of sustainability also included in the fourth component); (3) safety and technological resilience; (4) environmental, social and economic sustainability; and (5) governance, i.e. quality, transparency and accountability. Finally, the authors explored five energy security policy packages, targeting: (1) oil self-sufficiency, i.e. lessening dependence on foreign fuels; (2) energy affordability, i.e. maintaining cheap prices; (3) energy access, i.e. providing universal access to grids and services for heating and cooking; (4) climate change mitigation by reducing greenhouse gas emissions and lowering the carbon footprint of the energy sector; and (5) water availability, i.e. promoting forms of energy production that can operate in areas of water stress and scarcity.

In a paper on the energy security in Asia pacific, Sovacool (2011) presented the following dimensions of energy security identified by experts: availability, i.e. self-sufficiency; dependency, i.e. being energy independent (although the author noted that self-sufficiency may be a more pragmatic target); diversification, referring to variety and disparity; decentralization, i.e. small-scale energy; innovation, i.e. research and development; investment and employment; trade, encompassing geopolitics and interconnectedness; production, i.e. economic growth, reliability; price stability, including predictability; affordability, i.e. low cost, competition, subsidization, profitability; governance, including the concepts of transparency, accountability, legitimacy as well as resource curse; access, i.e. equity and energy poverty; reliability, i.e. safety; literacy, referring to education and quality of knowledge; resilience, i.e. stockpiling and adaptation; land use management; water quality and availability; ambient and indoor pollution and human health; energy efficiency, including conservation; and mitigation of greenhouse gas emissions.

In a paper synthesizing a framework for energy security, Sovacool and Mukherjee (2011) presented the following dimensions with corresponding components: (1) availability, i.e. security of supply and production, dependency and diversification; (2) affordability, i.e. price stability, access and equity, decentralization and affordability; (3) technology development and efficiency, i.e. innovation and research, safety and reliability, resilience and adaptive capacity, efficiency and energy intensity, and investment and employment; (4) environmental and social sustainability, i.e. land use, water, climate change, and pollution; and (5) regulation and governance, i.e. governance, trade and regional interconnectivity, competition and markets, and knowledge and access to information. The authors also presented a comprehensive list of simple, intermediate and complex indicators of different aspects of energy security.

In a paper assessing the energy security performance in the Asia Pacific from 1990 to 2010 and the aforementioned assessment of energy security in 18 countries from 1990 to 2010 (Sovacool, 2013), the following dimensions and components were listed (with some metrics mentioned as well): (1) availability with the components of security of supply, production, dependency and diversification; (2) affordability with the components of stability, access, equity and affordability; (3) technology development and efficiency with the components of innovation and research, energy efficiency, safety and reliability, and resilience; (4) environmental sustainability with the components of land use, water, climate change, and pollution; and (5) regulation and governance with the components of governance, trade and connectivity, competition, and information. Furthermore, in the assessment of energy security in 18 countries from 1990 to 2010, the author identified the following shortcomings of energy security index studies: (a) topical focus, either on industrial countries of the EU, OECD and North America or geared towards sustainable development and energy poverty; (b) scope and coverage, with many index studies being sector specific (e.g. electricity, oil, fossil fuels), ignoring geopolitical considerations, and utilizing unbalanced or limited metrics; (c) transparency, i.e. hiding underlying assumptions, dynamics and weights, so that indexes play the role of “Trojan horses … dressed a certain way to get inside the gates of energy policymaking.”; and (d) continuity, i.e. being snapshots rather than covering a number of years. Table 2.1 summarizes the most important energy security dimensions from the literature.

Table 2.1. Energy security dimensions

Authors	Dimensions
APERC (2007)	Availability, affordability, accessibility, and acceptability
Sovacool and Rafey (2011)	Availability, affordability, efficiency and development, and environmental and social stewardship
Knox-Hayes et al. (2013)	Availability, welfare, efficiency, affordability, environment, transparency, and climate
Sovacool, Cooper, & Parenteau (2011)	Availability, affordability, efficiency, and stewardship
5S’s	Surety, survivability, supply, sufficiency, and sustainability
Sovacool & Saunders (2014)	Availability, affordability, safety & technological resilience, sustainability, and governance
Sovacool (2011)	Availability, dependency, diversification, decentralization, innovation, investment and employment, trade, production, reliability, price stability, affordability, governance, access, literacy, resilience, land use management, water quality and availability, ambient and indoor pollution and human health, energy efficiency, and environment
Sovacool & Mukherjee (2011)	Availability, Affordability, Technology development and efficiency, Environmental and social sustainability, and Regulation and governance
Sovacool (2013)	Availability, affordability, technology development and efficiency, environmental sustainability, environmental sustainability, and regulation and governance

2.3.1. The role of renewable energy in the dimensions of energy security

Looking back at the dimensions of energy security proposed by Sovacool and Rafey (2011) the components of fuel diversification, disruption recovery, minimization of dependence on foreign supplies, minimization of price volatility, and support of sustainability (although with the introduction of aforementioned environmental impacts) are all served by the use of renewable energy for electricity production. Therefore, renewable energy improves the outlook of at least three of the four dimensions of energy security defined in that work. Recalling the definition of energy security by Knox-Hayes et al. (2013), it is argued that (further to the obvious connection of renewable energy to availability) that the components of environmental quality (especially climate change) and small-scale energy production may be improved by the use of renewable energy.

Turning to Sovacool and Mukherjee's (2011) work, the following components of security of supply and production should be favorably affected by renewable energy: dependency and diversification; price stability (regardless of the level of prices); decentralization and affordability (achieved with distributed small-scale installations); innovation and research (inherent in renewable energy); investment and employment (as new jobs are created in the renewable energy industry); environmental quality, especially climate change (with the aforementioned negative impacts of renewable energy); trade and regional interconnectivity (e.g. with onshore wind farms and distributed small scale systems).

Renewable energy probably provides the best opportunity for a country to become more independent of the vulnerabilities of global energy markets and approach the goal of energy self-sufficiency (Zhao, 2019), irrespective of its endowment in fossil fuel resources or its access to expensive nuclear energy technology. Considering Ren and Sovacool's (2014) mode detailed presentation of an energy security index, renewable energy entered the dimensions of: availability, as the percentage it represents of the total consumed energy; affordability, influencing the total energy produced by distributed and small scale generation (a characteristic of renewable installations); accessibility, by improving the outlook of safety and reliability (as a secondary source); acceptability, by helping with investment and employment.

The social acceptability of renewable energy has been reviewed by Stigka, Paravantis and Mihalakakou (2014) with empirical research carried out in a later work by Paravantis et al. (2018). The socioeconomic and environmental disadvantages of renewable energy are discussed, and the 2014 renewable energy performance is presented for EU countries, with Norway, Sweden, Latvia, Finland, Austria, Portugal and Denmark having high renewable energy usage and being near their targets (Stigka, Paravantis & Mihalakakou, 2014). The same source also points out that a number of social actors including local communities, local agencies, investors, nongovernmental organizations (NGOs), and local information networks, are involved in renewable energy projects. Opposition to projects is not uncommon, per the NIMBY (not in my back yard) phenomenon, which led the authors to review the following barriers to renewable energy projects:

- Economic and institutional factors, such as economic conditions in a region, issues with public or private ownership, lack of financial incentives, high investment costs (compared to fossil fuel alternatives), inefficiencies in the existing legal framework, complex licensing procedures and bureaucratic problems.
- Technical and planning factors, such as local geography and geomorphology, issues with the process of selecting an appropriate site (especially related to its previous usage), and planning problems.
- Environmental and quality of life issues, such as landscape deterioration, visual instruction, noise pollution and vibrations (related to the distance of residents from the renewable

energy installations), disruption of nearby ecosystems, impacts on the quality of life in the area.

- Factors related to public perceptions, such as lack of information or knowledge of renewable energy technologies, mistrust (intensifying with ignorance), lack of impartiality, and suspicion towards investors.

The latter empirical research (Paravantis et al., 2018) found out that income and awareness of renewables are strong determinants of the willingness to accept renewable energy. It was expected that aesthetics would be more of a problem near tourist destinations, where economic, social and cultural factors become involved Stigka, Paravantis, and Mihalakakou (2014). Nevertheless, it was found that considerations related to tourism were low in the list of factors affecting the willingness to pay for renewable energy projects (Paravantis et al., 2018). All in all, although renewable energy greatly improves the outlook on greenhouse gas emissions, reduces dependence on fossil fuels, and increases the safety and reliability of the energy supply, steps must be taken to facilitate acceptance by local communities Stigka, Paravantis and Mihalakakou (2014). Education and an improvement of the financial situation of families help build trust, so that the fear of uncontrolled development profiting at the expense of the public good is addressed.

3. Developing an energy security index

3.1. Introduction

An appropriate energy security index is required to evaluate each country's energy security level. A substantial amount of theoretical work has been conducted to investigate and quantify energy security in various countries and regions, using a variety of dimensions and methods. Geographical coverage depicts the energy security indexes generated for various regions and the spatial ranges to which those indexes can be applied. In general, there are three types of geographical coverage: (a) global coverage (WEF, 2016; WEC, 2018); (b) regional coverage, focusing on specific regions (e.g., Asian Pacific countries (Vivoda, 2010; Sovacool, 2011), the EU (Le Coq & Paltseva, 2009), or countries in the Organization for Economic Cooperation and Development (OECD) (IEA, 2007); and (c) that of specific countries (Zhang et al., 2013; Lyke et al., 2021).

The number of indicators used demonstrates the complexity of the index. The more indicators an index utilizes, the more difficult it is to collect data and compare. In general, a simple indicator is used to measure a specific aspect of energy security, while compound indicators take into account more complex and interrelated factors in the analysis of energy security. Usually analyses focus on the main dimensions of an index, with the emphasis highlighting the index's primary concerns (Yu, Li, & Yang, 2022).

3.2. Energy security indicators

According to Song, Zhang, and Sun (2019), a research strand on energy security is concerned with selecting energy security indicators corresponding to the definition of energy security. Some recent studies on energy security have produced multidimensional metrics or indicators for conceptualizing or measuring energy security (Ren & Sovacool, 2014). Several studies have suggested numerous indicators for measuring energy security, which can be used to compare a country's performance or monitor changes in its performance over time (Ang, Choong, & Ng, 2015a). The primary concern in these studies is how countries use quantitative indicators to assess their energy security. Assessing whether countries are responding adequately to emerging energy security challenges, such as climate change, increased reliance on fossil fuels, population growth, and economic development, is challenging without standard criteria (Esfahani et al., 2021).

The number of indicators determines the complexity of an index. Multiple indicators are usually required to represent the various dimensions of energy security (Gasser, 2020) and should be chosen after a thorough literature review. According to Ang, Choong, and Ng (2015a), when the number of indicators used is small, the energy security index is susceptible to changes in any of the indicators. A change in an indicator value can cause a significant swing in the index, raising the issue of index stability. When many indicators are used, most static indexes tend to dampen changes in individual indicator values.

However, the more indicators an index contains, the more difficult it is to collect and compare data. Because countries have different natural resources, political systems, economic welfare, ideologies, geographical locations, and international relations, many indexes that measure energy security have disparate indicator sets (Gasser, 2020). In general, a simple indicator focuses on a specific aspect of energy security, whereas compound indicators (i.e. indexes) cover more relative considerations in terms of analysis (Yu, Li, & Yang, 2022). Whereas some studies include a single indicator only, even 68 have been used by Augutis et al. (2012).

Foxon et al. (2002) determined that an indicator should be retained if it meets at least one of the following five criteria: comprehensiveness (i.e. the relevancy of the indicator for the measurement of the phenomenon); applicability (i.e. the applicability of the indicator to the selected countries); tractability (i.e. the sufficiency and the reliability of the available data to quantify the indicator); transparency (i.e. the transparency of the reasons for the selection of the indicator); and practicability (i.e. if the selected indicator set fulfill the purpose of the decisions to be assessed).

3.3. Energy security indexes

According to Gasser (2020), most existing energy security indexes are global, analyzing countries from different regions. This matches the notion that energy security is a global geopolitical issue (Yergin, 1988) and most countries are energy importers. Many indexes are sector-specific (designed solely for electricity, oil, or fossil fuels) and many focus on energy supply rather than demand. Geopolitical relationships and trade flows are rarely considered, and other dimensions, such as sustainability, equity, and efficiency, are frequently overlooked (Ren & Sovacool, 2014). According to Gasser (2020), many indexes are quantified for European, Asian, and North American countries. South American and African countries are under-reported.

The quantified indexes of studies that concern up to 30 countries primarily cover the EU member countries and countries from the OECD (Brown et al., 2014) or the world's major economies (Gasser, 2020). In general, surveys that cover more than 30 countries (this report covers 35) are all global assessments.

3.3.1. The US Chamber of Commerce Index

The US Chamber of Commerce (2020) index is a yearly indicator of energy risk. It identifies policies and other factors that contribute positively or negatively to US energy security using quantifiable data, historical trend information, and government projections. Chu et al. (2023) presented an index from the Global Energy Institute that utilizes available data and forecasts to represent the economic reliability, geopolitical risks, and environmental risks of a country's energy security. The index is made up of 29 individual indicators that are divided into eight broad categories: energy expenditures, energy use intensity, fuel imports, global fuels, the electric power sector, environmental quality, price and market volatility, and the transportation sector. The energy security risk index conveys the concept of risk by implying that a higher index indicates a more significant threat to national energy security and vice versa.

3.3.2. Energy Security Index (ESIOP)

In their study, Abdullah et al. (2021) assessed Pakistan's energy security performance by measuring its Energy Security Index (ESIOP) from 1991 to 2040. The index is made up of 39 indicators that have been finalized through discrimination analysis, reliability testing, and Principal Component Analysis (PCA).

3.3.3. China Energy Security Index (CESI)

Song, Zhang, and Sun (2019) developed a new aggregated indicator, the China energy security index (CESI), to assess how China's energy security has changed over time. The index includes three dimensions of energy security: energy supply, economic-technical, and environmental. The CESI and its sub-indexes were created by normalizing indicators from 1990, 1995, 2000, 2005, 2010, and 2014.

3.3.4. National Energy Security Index (NESI)

Sanchez, Segovia, and López (2023) examined the impact of Mexican national electricity on National Electric Security over a 50-year period, from 1970 to 2020, by estimating a National Energy Security Index (NESI). This research looks at four dimensions of analysis: availability, applicability, acceptability, and affordability. Each dimension is made up of a set of indicators that were constrained by the availability of data for Mexico. The index is composed of 19 indicators in total.

3.3.5. Oil Vulnerability Index (OVI)

The indexes that include up to 20 countries are primarily regional studies or studies of countries that belong to a similar group. Gupta (2008) introduced the Oil Vulnerability Index (OVI). Based on various indicators, OVI assessed the relative oil vulnerability of 26 net oil-importing countries.

3.3.6. Risky External Energy Supply (REES)

Le Coq and Paltseva (2009) developed the Risky EExternal Energy Supply (REES) index to assess the short-term risks associated with the external energy supply of EU member countries. The index combined measures of energy import diversification; political risks of the supplying country; energy transit risk; and the economic impact of supply disruptions. They created separate indexes for three primary energy types (oil, gas, and coal), and demonstrated that the supply risk exposure of member states varies by energy type.

3.3.7. Vulnerability Index

Gnansounou (2008) proposed a Vulnerability Index based on indicators such as energy intensity, reliance on oil and gas imports, the carbon dioxide (CO_2) content of primary energy supply, electricity supply weaknesses, and lack of diversity in transport fuels. The index was used to compare 37 industrialized countries. Using univariate clustering, the countries were ranged in three groups according to their composite vulnerability index: low, medium, and high.

3.3.8. ESIprice and ESIvolume

IEA (2007) defined indicators that focus on measuring the cause of energy insecurity. These indicators address two components of energy security independently: the price of energy (ESI_{price}) and its physical availability (ESI_{volume}). ESI_{price} is based on a measure of market concentration (ESMC) in each international fossil fuel market and calculates the relative importance of each ESMC value for a given country, based on the country's exposure to each fuel. The more a country is exposed to high concentration markets (i.e. markets in which many shares are concentrated between few firms), the lower its energy security becomes. ESI_{volume} measures a country's share of total energy demand met by oil-indexed, pipe-based gas imports, and is valuable mainly for the transportation of gas through pipelines. The greater this share, the less secure the country's gas supply.

3.3.9. Environmental Performance Index (EPI)

The Environmental Performance Index (EPI) is a data-driven summary of global sustainability. The EPI ranks 180 countries on climate change performance, environmental health, and ecosystem vitality, using 40 performance indicators across 11 categories. These indicators measure how close countries are to reaching established environmental policy targets on a national scale. Furthermore, the EPI provides practical guidance for countries that aspire to move toward a sustainable future (Wolf et al., 2022).

3.3.10. Energy Security Index (ESI)

Wang and Zhou (2017) proposed an energy security index for 162 countries, highlighting a country's ability to manage trade-offs across three dimensions: energy supply chain, energy consumption, and political-economic environment. Unlike most energy security evaluation frameworks in the literature, this study provided a new evaluation technique based on the integrated application of subjective and objective weight allocation methods introducing a balance score matrix highlighting how well a country manages the trade-offs between the three competing dimensions (energy supply chain, energy consumption, and political-economic environment) for evaluating global national energy security.

3.3.11. World Energy Trilemma Index (WEC)

Since 2010, the World Energy Council has been preparing an annual World Energy Trilemma Index (WEC). The World Energy Trilemma Index assesses 127 countries' energy performance across three dimensions: energy security, energy equity, and environmental sustainability. This index aims to provide insights into a country's relative energy performance across three dimensions. The energy trilemma index also seeks to educate policymakers, energy leaders, and the investment and financial sectors. Index rankings compare countries on each of the three dimensions, whereas historical indexed scores provide insights into each country's performance trends over time (WEC, 2022).

3.3.12. Energy Transition Index (ETI)

The Energy Transition Index (ETI) compares the performance of 115 countries' energy systems. The ETI provides decision-makers with a transparent fact based on the energy transition's progress and gaps and the transition's complexity and interdependence with social, political, environmental, economic, and institutional elements (WEF, 2021).

3.3.13. Energy Architecture Performance Index (EAPI)

The World Economic Forum (WEF) developed the Energy Architecture Performance Index (EAPI), which ranked 126 countries based on their ability to provide secure, affordable, and long-term energy (WEF, 2016). The 18 indicators covered energy security and access, sustainability, and contribution to economic growth and development. Since its inception, the EAPI has contributed to the global benchmarking of energy systems by highlighting current energy issues and providing guidance on making energy transitions more effective. By benchmarking the performance of national energy systems, the EAPI allows for cross-national comparisons.

3.3.14. Aggregated Energy Security Performance Index (AESPI)

The Aggregated Energy Security Performance Index (AESPI) by Martchamadol and Kumar (2013) was developed by considering 25 social, economic, and environmental indicators. AESPI requires time series data to compute and ranges from zero to 10. Through benchmarking a country's energy systems, the AESPI helps in evaluating its previous energy security condition and projecting its future status, taking into account the country's energy policies and plans, which facilitates monitoring policy outcomes.

3.3.15. Energy Security Index

The assessment time frame for creating an index varies significantly between studies. Wang and Zhou (2017), Le Coq & Paltseva (2009), Gnansounou (2008), and Gupta (2008) relied heavily on data from a single year. The energy security index developed by Sovacool and Brown (2010) was applied to 22 OECD countries for 1970 and 2007, covering large time ranges but calculating few values. Gasser (2020) points out that such studies enable researchers to compare current performance to previous ones. However, recent trends still need to be identified, so indexes with yearly updates are helpful. A workable compromise is calculating the index for fixed time intervals, such as every five years, as done by Ang, Choong, and Ng (2015b) and Sovacool et al. (2011).

3.3.16. US Energy Security Risk Index

A few studies in the literature make future projections and are typically quantified for a single country. The US Energy Security Risk Index is made up of 37 different energy security risk measures divided into nine categories: global fuels; fuel imports; energy expenditures; price and market volatility; energy use intensity; electric power sector; transportation sector; environmental; and basic science and energy research and development. The Index includes data from 1970 to 2019 and projections through 2040 (US Chamber of Commerce, 2020).

3.3.17. Energy Price Index (ESPI) and Energy Security Physical Availability Index (ESPAI)

Lefèvre's (2010) study defined two separate indexes: the energy security price index (ESPI) and the energy security physical availability index (ESPAI). The study examined ESPI and ESPAI in France and the United Kingdom and the evolution of both indexes through 2030.

Badea et al. (2011) proposed a methodology of building a composite indicator for energy security, which considers the decision maker's risk-averse level in a range varying continuously from risk-prone to risk-averse. This methodology allows for defining a threshold for a country's critical situation or a group of countries. Furthermore, it allows EU member states to be aware of the level of risk required to achieve an acceptable level of energy security.

Finally, studies that make future projections or scenario analyses necessitate a significant amount of effort in order to quantify the individual indicators. Only a few global studies provide recent yearly data to draw trends, and studies showing future projections are even rarer (Gasser, 2020).

3.4. Creating an energy security index

Indicator-based approaches are particularly well-suited to capturing the various dimensions of energy security given its multifaceted nature (Gasser, 2020). Because energy security is difficult to quantify using a single metric, various indicators are intended to represent its various dimensions (Ang, Choong, & Ng, 2015a). To assess the level of energy security, an index (i.e. a composite indicator) is calculated based on specific metrics, which are oftentimes grouped in dimensions (and possibly components).

Kruyt et al. (2009) suggested that no single indicator is ideal for measuring every dimension of energy security. Therefore, we made an effort to select a few appropriate indicators for each dimension. The decision on the number and nature of dimensions and the selection of indicators was based on previous research of UPRC on this topic (Paravantis, 2019; Kontoulis, Polymeropoulou, & Paravantis, 2019; Paravantis et al., 2018), the literature review carried out in this report, and data availability.

Figure 3.1 illustrates the selected dimensions and indicators for the geothermal energy security index.

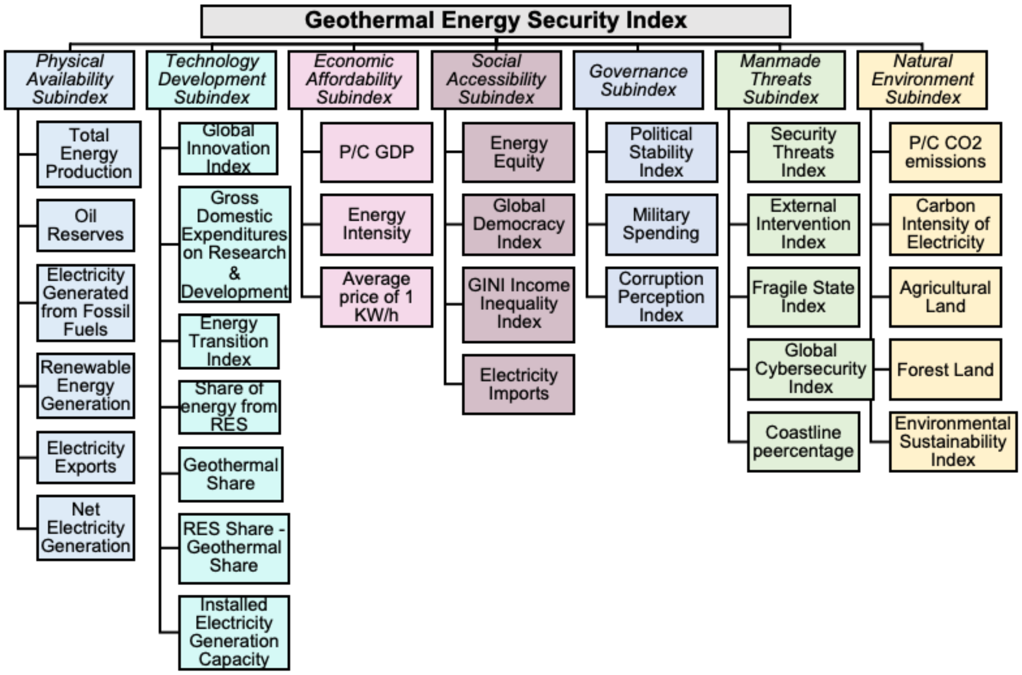

Figure 3.1. Geothermal energy security index: dimensions and indicators

Indicator data were collected for the year 2020. According to BP Statistical Review (2021), in 2020 global energy demand was estimated to have fallen by 4.5% in what was the worst recession since the end of World War II, caused by an unprecedented drop in oil demand as global lockdowns decimated transport-related demand. Natural gas demonstrated greater resilience, boosted primarily by China's continued strong growth. Renewable energy led by wind and solar energy, on the other hand, has continued to expand rapidly. As a result, the share of wind and solar generation in the global power mix increased at its largest rate ever.

The simple indicators and indexes were gathered from a variety of open sources, including the US Energy Information Administration (EIA), the World Factbook (CIA Factbook), the British Petroleum (BP Annual Statistical Review), the World Intellectual Property Organization (WIPO), the World Economic Forum (WEF), the World Bank, the Enerdata (World Energy & Climate Statistics), the World Energy Council (WEC), the Economist, the Our World in Database, Transparency International, and the ITUPublications. Some of the data were purchased from the Global Economy.

Given that the reliability of energy indicators is debated (Radovanović, Filipović & Pavlović, 2017), reliability is one of the most critical preconceptions for appreciating the relevance of the analysis in the context of energy policy and decision-making (Gogtay & Thatte, 2017). In this report, data reliability was the most important criterion for selecting countries for the creation of our index.

Details on the seven dimensions and indicators (33 in total) of the energy security index are shown in Table 3.1. An attempt was made to represent each dimension by a few useful and reliable indicators.

Table 3.1. List of dimensions and individual indicators for the Geothermal Energy Security Index formulation

Dimension	*Indicator*	*Acronym*	*Unit*	*Source*
1. Physical Availability	1.1. Total energy production (free)	TEP_quad	quad	EIA (US Energy Information Administration) (https://www.eia.gov/international/overview/world)
	1.2. Oil reserves (purchased)	OIL_RES_Bb	Billion barrels	The Global Economy (https://www.theglobaleconomy.com/download-data.php)
	1.3. Electricity generated from fossil fuels (free)	EL_GEN_FF_p100	% of total Installed capacity	The World Factbook (https://www.cia.gov/the-world-factbook/field/electricity-generation-sources)
	1.4. Renewable energy generation (free)	RES_GEN_TWh	TWh	British Petroleum (BP) (https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf)
	1.5. Electricity exports (purchased)	EL_EXP_TWh	TWh	The Global Economy (https://www.theglobaleconomy.com/download-data.php)
	1.6. Net electricity generation (free)	EL_GEN_TWh	TWh	Eurostat Statistics Explained https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_production,_consumption_and_market_overview#Electricity_generation

Dimension	*Indicator*	*Acronym*	*Unit*	*Source*
2. Technology Development Scenario Evaluation	2.1. Global innovation index (free)	GL_INNOV_INDEX	0-100	World Intellectual Property Organization (WIPO) (https://www.wipo.int/edocs/pubdocs/en/wipo_pub_gii_2020.pdf)
	2.2. Gross domestic expenditures on research and development (purchased)	EXP_R&D_pGDP	% of GDP	The Global Economy (https://www.theglobaleconomy.com/download-data.php)
	2.3. Energy transition index (free)	ET_INDEX	0-100	World Economic Forum (WEF) (https://www.weforum.org/reports/fostering-effective-energy-transition-2021/in-full/rankings)
	2.4. Share of energy from RES	RES_SHARE	%	Eurostat Statistics Explained https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Share_of_energy_from_renewable_sources,_2004-2021_(%25_of_gross_final_energy_consumption)V5.png
	2.5. Geothermal share (free)	GEO_SHARE	%	International Renewable Energy Agency (IRENA) https://www.irena.org/Energy-Transition/Technology/Geothermal-energy
	2.6. Installed electricity generation capacity (purchased)	EL_GEN_CAP_GW	GW	The Global Economy (https://www.theglobaleconomy.com/download-data.php)
3. Economic Affordability	3.1. GDP per capita (free)	GDPpc_USD	$/per capita	The World Bank https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?end=2020&start=2020&view=map
	3.2. Energy intensity (free)	EN_INT	koe/$15p	Enerdata (World Energy & Climate Statistics) (https://yearbook.enerdata.net/total-energy/world-energy-intensity-gdp-data.html)
	3.3. Average price of 1 KW/h (free)	PRICE1Kwh_USD	1KWh (USD)	cable.co.uk (https://www.cable.co.uk/energy/worldwide-pricing/)
4. Social Accessibility	4.1. Energy equity (free)	EN_EQUITY	0-100	World Energy Council (WEC) (https://www.worldenergy.org/publications/entry/world-energy-trilemma-

Dimension	*Indicator*	*Acronym*	*Unit*	*Source*
				index-2020)
	4.2. Global democracy index (free)	DEMOCR_INDEX	0-10	The Economist (https://www.economist.com/graphic-detail/2021/02/02/global-democracy-has-a-very-bad-year)
	4.3. GINI income inequality index (purchased)	GINI	0-1	Our World in Data (https://ourworldindata.org/grapher/economic-inequality-gini-index?time=2020)
	4.4. Electricity imports (purchased)	EL_IMP_TWh	TWh	The Global Economy (https://www.theglobaleconomy.com/download-data.php)
5. Governance	5.1. Political stability index (purchased)	POL_STAB_INDEX	-2.5 (weak) to 2.5 strong	The Global Economy (https://www.theglobaleconomy.com/download-data.php)
	5.2. Military spending (purchased)	MIL_SPEND_pGDP	% of GDP	The Global Economy (https://www.theglobaleconomy.com/download-data.php)
	5.3. Corruption perception index (free)	CPI	100=no corruption	Transparency International (The global coalition against corruption) (https://www.transparency.org/en/cpi/2020)
6. Manmade Threats	6.1. Security threats (purchased)	SEC_THREATS_INDEX	0 (low) to 10 (high)	The Global Economy (https://www.theglobaleconomy.com/download-data.php)
	6.2. External intervention index (purchased)	EX_INT_INDEX	0 (low) to 10 (high)	The Global Economy (https://www.theglobaleconomy.com/download-data.php)
	6.3. Fragile state index (purchased)	FRAG_STATE_INDEX	0 (low) to 120 (high)	The Global Economy (https://www.theglobaleconomy.com/download-data.php)
	6.4. Global cybersecurity index (free)	GLO_CYBSEC_INDEX	0 to 100	ITUPublications (https://www.itu.int/dms_pub/itu-d/opb/str/D-STR-GCI.01-2021-PDF-E.pdf)
	6.5. Percentage of coastline (free)	COASTLINE_p100	% of land	The World Factbook https://www.cia.gov/the-world-factbook/field/coastline
7. Natural Environment	7.1. CO_2 emissions per capita (free)	PC/CO2_t	tonnes	Our World in Data (https://ourworldindata.org/grapher/co-emissions-per-capita?tab=table&time=2020)

Dimension	*Indicator*	*Acronym*	*Unit*	*Source*
	7.2. Carbon intensity of electricity (free)	CARB_INT_gCO2e	gCO2e	Our World in Data (https://ourworldindata.org/grapher/carbon-intensity-electricity)
	7.3. Agricultural land (free)	AGR_LAND_p100	%	The World Factbook (https://www.cia.gov/the-world-factbook/field/land-use)
	7.4. Forest land (free)	FOR_LAND_p100	%	The World Factbook (https://www.cia.gov/the-world-factbook/field/land-use)
	7.5. Environmental sustainability index (free)	ENV_SUST_INDEX	0 to 100	World Energy Council (WEC) (https://www.worldenergy.org/transition-toolkit/world-energy-trilemma-index)

We attempted to balance the number of selected indicators based on data availability for each energy security dimension, which was not an easy task. Quantitative data sets were complete for the physical availability and economic affordability dimensions. However, only dimensionless data from existing indexes in the literature were available for the manmade threats dimension. Other dimensions contained both quantitative and dimensionless data.

3.4.1. Physical availability

The physical availability of energy (energy surety) is the historical bedrock of energy security. According to Ren and Sovacool (2014), the dimension of availability consists primarily of factors influencing a country's energy resources and energy supply security. The importance of energy availability stems from its ability to support economic and welfare growth. Economic expansion is hindered when availability is hindered and technological and consumption patterns change (Blum & Legey, 2012). For countries whose revenues are derived from energy exports, the demand dimension is as legitimate a concern as the resource parameter (Sovacool & Brown, 2010). From the standpoint of energy producers, energy security denotes a search for a market for their energy exports, which correlates to increased (government) revenues (Azzuni & Breyer, 2017).

The physical availability subindex is composed of the following six indicators: total energy production (1.1), oil reserves (1.2), fossil fuel electricity generation (1.3), renewable energy generation (1.4), electricity exports (1.5), and net electricity generation (1.6).

1. Total energy production of a country in 2020 is measured in quadrillion BTUs (quad) and refers to energy produced by any source.The data was derived from the U.S. Energy Information Administration (EIA).
2. Oil reserves are proven reserves of crude oil that geological and engineering data show are recoverable in future years from reservoirs under current economic and operating conditions. They are measured in billion barrels (bb) and the data were derived from the Global Economy data.

3. The indicator of electricity generated from fossil fuels refers to portfolios of fossil fuel-based electricity production, expressed as a percentage of a country's total installed capacity. The data were derived from the World Factbook.
4. The renewable energy generation indicator measures the electricity produced by renewables in terawatt-hours (TWh). The data were derived from the British Petroleum (BP) statistical review.
5. The electricity exports indicator measures annual electricity exports in TWh and the data were derived from the Global Economy data.
6. Finally, net electricity generation data in TWh was added from Eurostat Statistics to describe electricity generation by various energy sources.

3.4.2. Technology development

The second dimension represented technology development. Because technology is required for energy utilization, energy security is inextricably linked to technological development, both directly and indirectly. In this regard, new technological solutions for manufacturing, transportation, conversion, storage, and distribution impact energy security. As a result, new technologies provide new energy sources, increasing energy security.

The subindex consists of seven indicators: global innovation index (2.1), gross domestic expenditures on research and development (2.2), energy transition index (2.3), share of energy from RES (2.4), geothermal share (2.5), installed electricity generation capacity (2.6), geothermal installed capacity potential (2.7), with values available for depth ranges 3 to 5, 3 to 7, and 3 to 10 km respectively.

1. The Global Innovation Index (GII) tracks the world's most innovative economies, ranking the innovation performance of around 132 economies and highlighting innovation strengths and weaknesses. The index includes approximately 80 indicators, encompassing measures of each economy's political environment, education, infrastructure, and knowledge creation. Good infrastructure, like strategic stocks, is required for stable energy supplies and is an important component of economic energy security (APERC, 2007). The various metrics provided by the GII aid in monitoring performance and benchmarking development against economies in the same region or income group. The index score ranges from 0 to 100, with 100 representing the most positive value a state can achieve. The data were derived from the World Intellectual Property Organization (WIPO).
2. The gross domestic expenditures on research and development are expressed as a percent of GDP. They include capital and current expenditures in the four main sectors: business enterprise, government, higher education, and private non-profit. Basic research, applied research, and experimental development are all part of research and development. The data were derived from the Global Economy data.
3. The Energy Transition Index (ETI) measures how well a country is progressing in its energy transition. It considers current conditions and how conducive the country is to the future adoption of renewables. The index ranges from 0 to 100, with 100 being the most positive value a state can achieve. The data was derived from the World Economic Forum (WEF).

4. The data for energy share from RES as a percentage of total final energy consumption were obtained from Eurostat.
5. The International Renewable Energy Agency (IRENA) provided the geothermal percentage share data.
6. The Installed Electricity Generation Capacity indicator is measured in gigawatts (GW). The data were retrieved from the Global Economy data.
7. Lastly, the indicator Geothermal Power Capacity Potential expresses the technical potential of geothermal energy production in GW for respective depth ranges of 3 to 5, 3 to 7, and 3 to 10 km, with data provided by (Chamorro et al., 2013).

3.4.3. Economic affordability

The dimension of economic affordability is crucial due to the significant correlation between energy and the economy. Volatile fossil fuel prices can complicate energy supply security and limit the ability of policymakers to plan for capacity expansion and other short-term measures (Ang, Choong, & Ng, 2015a).

For the calculation of this subindex, three indicators were chosen: GDP per capita (3.1), energy intensity (3.2), and average price of 1 KW/h (3.3).

1. The GDP per capita indicator shows the Gross Domestic Product divided by midyear population. GDP is calculated as the sum of the gross value added by all resident producers in the economy, plus any product taxes, and minus any subsidies not included in the product value. It is calculated without making deductions for the depreciation of fabricated assets or for the depletion and degradation of natural resources. Data are in current US$ and were derived from the World Bank.
2. Energy intensity is calculated as the ratio of total physical primary energy supply (TPES) over GDP (Böhringer & Bortolamedi, 2015). A country's economic structure and the design and scale of the underlying energy efficiency policies influence the evolution of energy intensity (Azhgaliyeva, Liu, & Liddle, 2020). To improve energy security, energy intensity should be reduced (reducing the economy's dependence on energy) (Azzuni & Breyer, 2017). The energy intensity indicator is calculated by dividing a country's total energy consumption by GDP. It calculates the total energy required to produce one unit of GDP. Coal, gas, oil, electricity, heat, and biomass are all components of total energy consumption. GDP is expressed at constant exchange rates and purchasing power parity (PPP) to eliminate the impact of inflation, reflect differences in general price levels, and relate energy consumption to the actual level of economic activity. Using PPP rates for GDP instead of exchange rates, raises the value of GDP in low-cost-of-living regions, lowering energy intensities. The data is calculated in kilograms of oil equivalent per USD at the constant exchange rate, price, and PPP of 2005 (koe/$15p) and were derived from Enerdata (World Energy & Climate Statistics).
3. Finally, the average price of 1 KW/h shows the price of electricity per kilowatt-hours (kWh) in US$ for each country. The data were derived from cable.co.uk.

3.4.4. Social acceptability

Social acceptability represents social stewardship. It consists of four indicators: energy equity (4.1), the global democracy index (4.2), the GINI inequality index (4.3), and electricity imports (4.4).

1. The energy equity indicator assesses a country's ability to provide universal access to reliable, affordable, and abundant energy for domestic and commercial use (Ren & Sovacool, 2014). It includes basic access to electricity and clean cooking fuels and technologies, as well as access to prosperity-enabling levels of energy consumption and electricity, gas, and fuel affordability. The index's score ranges from 0 to 100, with 100 representing the most positive value a state can achieve. The data were derived from the World Energy Council (WEC).
2. The global democracy index is based on 60 indicators divided into five categories that measure pluralism, civil liberties, and political culture. The index assigns each country a numeric score and a ranking, categorizing it into one of four regime types: full democracies, flawed democracies, hybrid regimes, and authoritarian regimes. The index's score ranges from 0 to 10, with 10 being the most positive value a state can achieve. The data were derived from the Economist Intelligence Unit (2022).
3. The GINI inequality index used in this report measures the inequality of income distribution in a population. Its values range from zero to one, with higher values indicating more inequality. The data were derived from Our World in Data.
4. Finally, electricity imports are measured in TWh per year using data from the Global Economy data.

3.4.5. Governance

Governance is the fifth analysis dimension. Sound government policies aid in mitigating and hedging against energy disruptions. Governance is an important dimension at a time when countries are increasingly engaged in energy diplomacy, with foreign policies aimed at ensuring energy supplies from exporting regions (Ang, Choong, & Ng, 2015a).

According to Ren and Sovacool (2014), governance can be divided into two categories: national and international. The ability of national institutions to govern and regulate the energy sector is measured by national governance. International governance assesses a country's compliance with international governance norms such as rule of law and low corruption.

The subindex includes three indicators: the political stability index (5.1), military spending as a percent of GDP (5.2), and the corruption perception index (5.3).

1. Political stability indicates the durability and stability of domestic political institutions (Ren & Sovacool, 2014). Furthermore, because governments control either the actual energy supply or the conditions under which other parties develop it, the political situation in supplier countries is critical to the security of the energy supply (Kruyt et al., 2009). The Political Stability Index used in our governance subindex assesses the likelihood that the government will be destabilized or overthrown through unconstitutional or violent means,

such as politically motivated violence and terrorism. The index is a weighted average of several other indexes, including those from the Economist Intelligence Unit, the World Economic Forum, and the Political Risk Services. Its values range from −2.5 (weak) to 2.5 (strong).

2. The military relies heavily on energy, and it is crucial to address their interdependence across various levels. Peacekeeping, defense ministries, paramilitary forces, and military space activities are all included in the military spending indicator (as a percentage of GDP). Retirement pensions, operations and maintenance, procurement, military research and development, as well as military aid are accounted for. Political stability and military expenditure data were derived from the Global Economy data.
3. Finally, the corruption perception index ranks countries based on perceived corruption in their public sector. The results are presented on a scale from 0 to 100, where 0 indicates a high level of corruption and 100 indicates a very low level of corruption. The data were derived from Transparency International.

3.4.6. Manmade threats

The manmade threats dimension represents threats to energy infrastructure. It consists of five indicators: the security threats index (6.1), the external intervention index (6.2), the fragile state index (6.3), the global cybersecurity index (6.4), and the percentage of coastline (6.5).

1. The security threats index is an indicator that considers security threats such as bombings, attacks, battle-related deaths, rebel movements, mutinies, coups, or terrorism. The security apparatus also considers severe criminal factors such as organized crime, homicides, and the perceived trust of citizens in domestic security. The higher the index, the greater the threats. Data for this index were derived from the Global Economy data.
2. The external interventions index is a metric that measures the influence and impact of external actors on the functioning of a state, particularly its security and economic performance. The greater the index, the greater the external intervention in the country. Data for this index were also derived from the Global Economy data.
3. The fragile state index measures vulnerability in three stages: pre-conflict, active conflict, and post-conflict.The index includes 12 conflict risk indicators that are used to assess the current situation of a state: security apparatus, factionalized elites, group grievance, economic decline, uneven economic development, human flight, brain drain, state legitimacy, public services, human rights and the rule of law, demographic pressures, refugees and IDPs, and external intervention. The higher the index, the more fragile the state. Data for this index were also derived from the Global Economy data.
4. The International Telecommunication Union (ITU) launched the Global Cybersecurity Index (GCI) in 2015 to measure the commitment of 193 ITU Member States and the State of Palestine to cybersecurity, help them identify areas for improvement, and encourage states to take action by raising awareness about cybersecurity globally. As cybersecurity risks, priorities and resources change, the GCI provides a more accurate picture of the

cybersecurity efforts of a state (ITU, 2021). Because all energy infrastructures now rely on digital support, the digital dimension is regarded as essential for ensuring energy security. Any failure in the cyber dimension will affect the energy system. Data for this index were also derived from the Global Economy data.

5. Geographic permanence, such as the length of a country's coastline or the absence of direct access to the high seas, modifies seapower in general and maritime security policies in particular (Germond, 2015). The percentage of coastline was added to demonstrate the security disadvantages (or even advantages, considering the stopping power of the sea) of having shorter land borders for a country. Landlocked countries (like Austria, Hungary, Luxembourg, Slovakia, and Switzerland) are surrounded by other countries and thus have no coastline providing access to the sea. Data was retrieved from the World Factbook.

3.4.7. Natural environment

The natural environment is the last dimension of our energy security index. This reflects the fact that energy systems are seen as being inextricably linked to the environment, both in terms of their impact on the environment and the ways in which environmental issues, such as climate change, constrain them.

This dimension includes five indicators: CO_2 emissions per capita (7.1), carbon intensity of electricity (7.2), agricultural land (7.3), forest land (7.4), and the environmental sustainability index (7.5).

1. CO_2 emissions per capita are an indicator of a country's average per capita contribution and are expressed in per capita CO_2 tonnes. The data were retrieved from Our World in Data, a scientific online publication focusing on global issues.
2. Carbon intensity is a metric used to measure the amount of greenhouse gasses, measured in grams of CO_2 equivalent (gCO2e), emitted per kilowatt-hour of electricity produced. The information is derived from Our World in Data.
3. The agricultural land indicator quantifies the percentage of agricultural land of a country, with data derived from the World Factbook.
4. The forest land indicator equals the percentage of land covered by forests in a given country, with data also derived from the World Factbook.
5. Finally, the Environmental Sustainability Index reflects a country's progress in transitioning its energy system to mitigate environmental impacts and climate change. The environmental dimension is part of three trilemma dimensions: energy security, energy equity, and environmental sustainability. This dimension focuses on productivity and efficiency of generation, transmission and distribution, decarbonization, and air quality. The higher the value of the index, the more environmentally sustainable the country is. The data were gathered by the World Energy Council (WEC).

4. Analysis and results

This section presents the analysis and results of the estimation of the energy security index and its various dimensions.

4.1. Country sample

Energy security cannot be evaluated in isolation, because nearly every country depends on products from another at some stage in the energy supply chain (Gasser, 2020). Following the study of Brown et al. (2014), we developed our energy security index to evaluate individual countries rather than regional blocs. This is because the country remains the site of most energy planning and policymaking and the source of the vast majority of significant energy statistics based on national borders.

Table 4.1 lists the 35 countries whose energy security is evaluated in this report. Twenty-six of these 35 countries are European Union (EU) members. The list also includes Iceland, Norway, Switzerland, the United Kingdom, the US, Russia, China, India, and Turkey.

Table 4.1. Countries examined for the Geothermal Energy Security Index

List of countries		
1. Austria (EU member)	13. Greece (EU member)	25. Portugal (EU member)
2. Belgium (EU member)	14. Hungary (EU member)	26. Romania (EU member)
3. Bulgaria (EU member)	15. Iceland (Europe)	27. Russian Federation (Asia)
4. China (Asia)	16. India (Asia)	28. Slovakia (EU member)
5. Croatia (EU member)	17. Ireland (EU member)	29. Slovenia (EU member)
6. Cyprus (EU member)	18. Italy (EU member)	30. Spain (EU member)
7. Czech Republic (EU member)	19. Latvia (EU member)	31. Sweden (EU member)
8. Denmark (EU member)	20. Lithuania (EU member)	32. Switzerland (Europe)
9. Estonia (EU member)	21. Luxembourg (EU member)	33. Turkey (Middle East)
10. Finland (EU member)	22. Netherlands (EU member)	34. United Kingdom (Europe)
11. France (EU member)	23. Norway (Europe)	35. USA (North America)
12. Germany (EU member)	24. Poland (EU member)	

The selected countries accounted for 66.6% of global energy consumption in 2020, with China leading the way with 26.1% (US 15,8%, Europe 13,9%, India 5,7%, and Russia 5,1%) (BP, 2021). Furthermore, they were responsible for 67.3% of global CO_2 emissions, with China once again leading the way with 30.7% (US 13.8%, Europe 11.1%, India 7.1%, and Russia 4.6%). Finally, they accounted for 79.1% of global renewable energy generation, with European countries and China leading the way with 29,3% and 27,4%, respectively (US 17,5%, India 4,8%, and Russia 0.1%). According to BP's assessment, primary energy refers to commercially traded fuels, as well as modern renewables that are utilized for electricity production. The carbon emissions measured only account for those generated through the use of oil, gas, and coal for combustion-related processes and flaring of natural gas.

4.1.1. United States of America

The US has been a world leader in geothermal energy generation. The energy security of the US has improved significantly in recent years due to increased domestic production of oil and natural gas and the expansion of RES such as wind and solar power. The US is currently one of the world's largest oil and natural gas producers, with significant reserves of fossil fuels in shale formations throughout the country. Nevertheless, global supply disruptions or price spikes can still impact the US economy and national security. In addition, the US electricity grid is vulnerable to cyberattacks, physical attacks, and natural disasters, which can disrupt the flow of electricity and threaten the country's energy security. The US government and industry are working to address these vulnerabilities and improve the resilience of the nation's energy infrastructure. The US has significant geothermal potential, particularly in western states with active geothermal systems. The total technically recoverable geothermal resource in the US is estimated to be over 60 GW of installed capacity (US Department of Energy, 2018).

4.1.2. Russian Federation

Russia is a significant player in the global energy markets, and one of the world's top crude oil producers, competing with Saudi Arabia and the US for first place. Russia's energy security largely depends on its vast oil and natural gas reserves, which are critical drivers of the country's economy, while its oil and natural gas revenues accounted for 45% of its 2021 federal budget (IEA, 2022). According to the International Energy Agency's Atlas of Energy, Russia had the highest percentage of overall energy self-sufficiency (191%) after Norway. Nevertheless, Russia's heavy reliance on hydrocarbons has left its economy vulnerable to global oil and gas price fluctuations. Limited investment in RES and outdated energy infrastructure pose concerns about its energy security. To address these challenges, Russia has sought to diversify energy exports and pursued strategies such as investing in new oil and gas fields, modernizing infrastructure, and developing nuclear and RES. Russia has more than 1000 hot springs and about 100 geothermal fields, with a total estimated capacity of 83.9 MW, which produced 428 million kWh of electric energy in 2019 (Butuzov et al., 2022). Despite the significant geothermal potential in regions such as Kamchatka and the Kuril Islands, only a small fraction is utilized for power and heating due to low energy prices, oil and gas dominance, and government support. However, recent efforts have been made to promote geothermal energy, including pilot projects and feasibility studies, and the government has implemented incentives for geothermal exploration and development.

4.1.3. China

According to the EIA's latest report (August 2022), China was the world's most populous country in 2020 (1.411 billion) with a rapidly growing economy. Because of their sheer size and growth rate, both China and India are transforming global energy markets, while rising Chinese and Indian demand is impacting the global energy market significantly (Vivoda, 2010). The Chinese economy has pushed a rapid increase in energy demand, resulting in a growing gap between domestic energy supply and demand, as well as an increasing reliance on energy imports (Zhang et al., 2017). Given the expectation that China's energy demand will continue to rise, it is necessary to evaluate its energy security. Given its position as the world's largest energy consumer and producer, China's energy security is a multifaceted issue. The country’s dependence on domestic coal production as well as imports of oil and natural gas, poses potential vulnerabilities. China has invested in RES, improved energy efficiency, and secured access to overseas resources to address this. China’s geothermal resources account for 7.9% of global geothermal resources (Wang et al., 2020). China also possesses significant untapped geothermal energy potential, estimated at 860,000 MWt. However, only a small fraction of this is currently being used for power generation and heating. To increase utilization, the Chinese government has promoted geothermal development with policies and financial incentives, aiming to enhance the exploitation of the country's geothermal potential (Hu, Cheng & Tao, 2021). As a result, China’s energy plan and strategy will increasingly impact global energy market competition and raise concerns about energy security (Song, Zhang, and Sun (2019).

4.1.4. India

With about 1.4 billion people, India is the world’s most populated country. According to the BP Statistical Review of World Energy 2021, India was the world’s third-largest energy consumer after China and the US in 2020. India’s energy security is a critical issue due to the country’s rapid economic growth and increasing energy demand. The majority of India’s energy comes from coal, oil, and gas, which are largely imported, making the country vulnerable to fluctuations in global energy prices. To address this, India has taken several measures to enhance its energy security, including promoting domestic production of coal, oil, and gas, investing in RES such as solar and wind power, and improving energy efficiency. India also has significant geothermal potential, particularly in the western and northwestern regions of the country. However, geothermal energy is still in its nascent stage of development in India, and only a small fraction of its potential is currently being utilized. According to India’s energy profile (IRENA, 2022), electricity generation from geothermal energy in 2020 was 0%. To promote geothermal development, the government has implemented policies to encourage private sector investment in geothermal exploration and development, including tax incentives and subsidies, and envisioning achieving at least 10 GW of installed geothermal capacity by 2030, as Puppala et al. (2022) claim.

4.1.5. European Union

The EU is concerned about energy security due to its dependence on imports, particularly natural gas from Russia (especially after Russia’s invasion of Ukraine). The EU aims to reduce reliance on fossil fuels and promote renewable energy, including geothermal energy, which has the potential for both electricity generation and heating. However, the current installed capacity of geothermal energy in the EU is limited to 24.3 GW_{th} for heating and cooling, and high-enthalpy resources in limited regions are mainly used for geothermal energy harvesting (Fink, Heim and Klitzsch (2022). According to the same survey, to fully unlock geothermal energy’s potential, it is crucial to utilize low-to-medium enthalpy resources in less favorable regions, accounting for most of Central Europe’s geothermal potential. By the year 2050, the estimated EU economic power generation prospect from Enhanced Geothermal Systems (EGS) is projected to be around 2570 terawatt-hours (TWh) (Alsaleh & Wang, 2023). Several EU member countries including Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden are examined in this context.

4.1.6. United Kingdom

Turning to non-EU countries, the UK is a significant economic and geopolitical player with a diversified energy mix that includes natural gas, nuclear, coal, and renewables. According to the Office for National Statistics (2022), over half of the country's gas consumption is imported from Norway, Qatar, US, and Russia, creating risks and vulnerabilities. The British government is implementing policies to promote renewable energy, reduce reliance on fossil fuels, and invest in energy storage technologies. In their study, McClean and Pedersen (2023) highlight that the geothermal potential of the UK is underutilized, making up just 4.5% of the renewable energy used in the country. However, it has been estimated that the UK has sufficient accessible geothermal resources to meet its current heating requirements for approximately 100 years (as well as 9% of England's and 85% of Scotland's annual electricity requirements).

4.1.7 Switzerland

Switzerland was included in the list due to its ranking as the EU's fourth largest trading partner in 2020, following China, the US, and the UK. Switzerland's energy mix is well-diversified, with hydropower and nuclear energy as the primary sources of electricity. The country aims to increase the share of renewable energy and reduce dependence on fossil fuels and nuclear power. Switzerland has a developed energy infrastructure and significant geothermal potential in the Alpine region. However, geothermal energy development faces challenges such as high drilling costs and limited locations. Despite having limited high-enthalpy geothermal resources, Switzerland has become a leading country in geothermal research and development. The Swiss government has taken steps to encourage geothermal energy development through funding and incentives. The country has launched new projects, developed underground laboratories, and fostered collaboration between research and industry partners to address new challenges in the sector. According to Lupi (2023), the geothermal roadmap for Switzerland aims to provide 2 TWh of energy (up to 18 TWh if heat is included) by 2050.

4.1.8. Norway

Norway is a significant player in the global energy market, with the majority of its energy supply coming from its vast oil and gas reserves. Norway was chosen due to the high growth rate in renewable energy generation in 2020 (73.4% from 2019 to 2020) (BP, 2021). The country's overall energy self-sufficiency rate was 727% (IEA Atlas of Energy). Despite Norway's reliance on hydrocarbons, it has taken measures to enhance its energy security by diversifying its energy mix and investing in RES like hydropower, wind power, and bioenergy. Additionally, Norway's well-developed energy infrastructure with extensive interconnections with neighboring countries allows it to import and export energy as needed. However, only a small fraction of its geothermal potential is currently being utilized for heating purposes. The development of geothermal energy in Norway has been slow due to high exploration and drilling costs, a lack of government support, and the oil and gas industry's dominance. However, recent years have seen growing interest in promoting geothermal energy, with several pilot projects and research initiatives underway. The Norwegian government has provided tax incentives and funding for exploration and development (Kvalsvik, Midttømme & Ramstad, 2019) point out.

4.1.9. Iceland

Iceland is a leading country in geothermal energy production in Europe. The country has a high proportion of geothermal energy generation (32.3% of total installed capacity in 2020) (The World Factbook, 2020). Iceland has a unique energy security situation due to its abundant RES, including geothermal and hydropower. The country produces almost all of its electricity from these sources, which has allowed Iceland to achieve energy independence and reduce its reliance on imported fossil fuels. Iceland's energy security is also enhanced by its small population and limited energy demand. However, Iceland is vulnerable to natural disasters such as volcanic eruptions and earthquakes, which could disrupt energy production and supply. To address this, the country has invested heavily in infrastructure to ensure the stability and resilience of its energy systems. Iceland's geothermal potential is particularly significant, and the country has become a global leader in geothermal energy development and technology. As of 2021, geothermal energy provides approximately 25% of Iceland's electricity and almost 90% of its heating needs (Kjeld, Bjarnadottir & Olafsdottir, 2022).

4.1.10. Turkey

Finally, despite not being a producer, Turkey was chosen as it is a vital oil and gas transit country between Asia and Europe. Turkey's energy security is influenced by its heavy reliance on imported energy resources, particularly oil and natural gas. The country has implemented various measures to reduce this dependence and diversify its energy mix, including promoting the use of RES such as wind, solar, and geothermal. At the same time, Turkey has significant geothermal energy potential, with an estimated capacity around 4 GW by 2030 for electricity generation (Lise & Uyar, 2022). The government has taken steps to encourage geothermal energy development, including offering incentives for investment and research and development. The country also has plans to expand its nuclear power capacity and increase domestic coal production. However, Turkey's energy security remains vulnerable to fluctuations in global energy prices and geopolitical tensions.

It is noted that the country list was narrowed down to a smaller group of 19 countries for scenario projections, chosen for their available time series data on selected indicators. These 19 countries include Austria, Belgium, China, Denmark, France, Greece, Iceland, India, Ireland, Italy, Netherlands, Norway, Norway, Portugal, Spain, Sweden, Switzerland, the United Kingdom, Turkey, and the US. Interesting highlights of some of those countries are discussed below.

4.2. Quantitative techniques

After selecting and grouping the appropriate indicators to formulate our energy security index, the next step is to calculate a composite index for each of the selected countries. The calculation process is divided into the following steps:

1. Normalizing the simple indicators;
2. Aggregating the normalized simple indicators within each dimension to find a subindex for each dimension;

3. Aggregating the normalized subindexes of each dimension into a single energy security index, using appropriate weights for each dimension.

Because the raw data of the indicators of each dimension are in different units and cover different numerical ranges, normalizing them allows meaningful comparisons (Ang, Choong, & Ng, 2015a; Narula et al., 2017; Amin et al., 2021). Depending on the number of indicators used, the countries involved, and the normalizing methods, different studies may use different approaches (Abdullah et al., 2021). Among the various normalization methods described in the literature, such as distance to a reference, min-max, and banding method, we will use z-score standardization. Normalization converts all indicators to a common scale, enabling them to be weighted and combined into a dimensional subindex (Gasser, 2020).

Each dimensional subindex can be assigned a weight using either objective or subjective methods. There are several objective methods for weighting indicators in the literature, including PCA, Data Envelopment Analysis, Analytic Hierarchy Process, and the equal weights method. Weights can also be determined using various knowledge elicitation methods, such as surveys, interviews, and the Delphi method.

Finally, the dimensional subindexes can be weighted and aggregated into a composite index. The literature on composite indicators offers several examples of aggregation techniques. The most commonly used additive techniques range from summing up country rankings in each indicator to aggregating normalized indicators with appropriate weights. Song, Zhang, and Sun (2019) reported that additive aggregation has been used in over 80% of the existing literature on energy security indexes. One reason for its popularity is that it is easy to apply and understand, as noted by Gasser (2020).

4.2.1. Normalization of indicators

The methodology used to construct energy security indicators is constrained by data availability for the selected countries. As a result, we gathered information from a variety of sources. Since no weighting was applied to the 33 indicators, a significant change in a single attribute could dominate a country's energy security index. We mitigated these effects by using z-score normalization followed by factor analysis, as proposed by Brown et al. (2014).

Standardization is a popular method (Ang, Choong, & Ng, 2015a). Martchamadol and Kumar (2012) used the normal distribution z-scores method to standardize all the indicators in their research. The standardization method is a linear transformation of the data set that results in a normalized data set with a mean of zero and a standard deviation of one. It preserves the distribution of the indicator values, and the data set is not bounded by fixed minimums and maximums (Gasser, 2020). Z-scores indicate the normalized distance of data points from the mean in terms of standard deviation units:

$$z\text{–}score = \frac{X - \mu}{\sigma}$$

where X represents the raw value of an indicator for a single country, μ is the mean (average) of the raw values of the indicator for all countries, and σ is the standard deviation of the raw values of the indicator for all countries.

Ang et al. (2015a) suggested using this method when investigating a large number of countries, as in our case where we examine 35 countries. Z-scores are dimensionless quantities that indicate how many standard deviations a country is above or below the mean of the 35 selected countries. Z-scores are useful for identifying the divergence of individual countries and groups of countries from underlying trends, as they evaluate the relative magnitude of change in indicators.

4.2.2. Aggregation of normalized indicators within each dimension

Aggregation is the process of combining normalized data into a single score, and it is done within each dimension in order to calculate seven dimensional subindexes as well as using weights to generate an overall energy security index score for each country.

The normalized indicators within each dimension were aggregated by adding, without using any weights.

Our research focused on the simple aggregation method, based on the premise, as Rodríguez-Fernández, Carvajal, and Ruiz-Gómez (2020) proposed that a compound index is obtained as the weighted sum of the changes in the individual series used. The index's main comparative advantage over others is that it only measures energy security for geothermal energy.

4.2.3. Weighting of normalized indicators

To assign weights to each dimensional subindex, we utilized the Delphi method. We formed a panel of energy experts with diverse backgrounds in global politics, economics, environmental issues, and engineering. The expert panel included academic faculty with significant EU experience, as well as senior professionals, including diplomats, with expertise in energy (including geopolitics, state actors, and small businesses), economics (including transportation), technology (including networks and cybercrime), and the environment (including water).

The experts were asked to rate the importance of the seven energy security dimensions at various historical milestones. The average rating is shown in Figure 4.1.

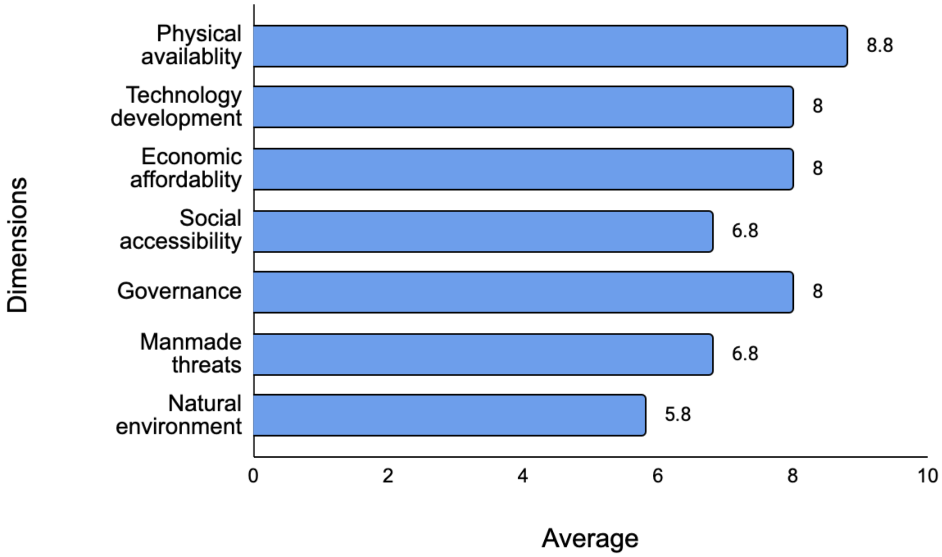

Figure 4.1. Importance of energy security dimensions

We acknowledge that the average ratings we used to assign weights to each dimension are not necessarily the most accurate representation of the importance of each dimension for all countries and historical periods. The optimal weight of each dimension may vary depending on specific country contexts and changing global circumstances. Nonetheless, these weights serve as a pragmatic starting point in our endeavor to construct a comprehensive energy security index.

This work serves as the initial phase of research, which will be expanded in Task 3.4 to include expert interviews and add a geopolitical perspective. For that task, we will select a diverse panel of junior and senior academic researchers and practitioners who specialize in policy areas such as energy, renewable energy, geothermal energy, energy economics, energy security, and geopolitics. We will also include officials from relevant government departments and bodies. The panel members will be requested to assess the significance of the seven dimensions of the geothermal energy security index, in relation to the targeted technological advancements in deep geothermal drilling by ORCHYD. They will also be asked to identify any potential oversights or overlaps in the approach of WP3 and suggest ways to enhance the meaning of the energy security index and its relation to geothermal energy.

4.2.4. Calculation of final index

The energy security index is calculated from the seven subindexes representing the dimensions of energy security: (1) physical availability subindex, (2) technology development subindex, (3) economic affordability subindex, (4) social accessibility subindex, (5) governance subindex, (6) manmade threats subindex, and (7) natural environment subindex.

The subindexes are calculated according to the following formulas, with the signs of each z-score indicate whether the corresponding indicator is considered to increase (plus sign) or decrease (minus sign) energy security:

$$\begin{gathered}\text{PHYSICAL AVAILABILITY SUBINDEX} = \\ (\text{z-score}_{\text{TEP}}+\text{z-score}_{\text{OIL\_RES}}+\text{z-score}_{\text{EL\_GEN\_TWh}}+ \\ \text{z-score}_{\text{RES\_GEN}}+\text{z-score}_{\text{EL\_EXP}}-\text{z-score}_{\text{EL\_GEN\_FF}})/6\end{gathered}$$

$$\begin{gathered}\text{TECHNOLOGY DEVELOPMENT SUBINDEX} = \\ (\text{z-score}_{\text{INNOV\_INDEX}}+\text{z-score}_{\text{EXP\_R\&D\_pGDP}}+\text{z-score}_{\text{ET\_INDEX}}+ \\ \text{z-score}_{\text{EL\_GEN\_CAP\_GW}}+\text{z-score}_{\text{GEO\_SHARE}}+\text{z-score}_{\text{RES-GEO}})/6\end{gathered}$$

$$\begin{gathered}\text{ECONOMIC AFFORDABILITY SUBINDEX} = \\ (\text{z-score}_{\text{GDPpc\_USD}}-\text{z-score}_{\text{EN\_INT}}-\text{z-score}_{\text{PRICE1Kwh\_USD}})/3\end{gathered}$$

$$\begin{gathered}\text{SOCIAL ACCESSIBILITY SUBINDEX} = \\ (\text{z-score}_{\text{EN\_EQUITY}}+\text{z-score}_{\text{DEMOCR\_INDEX}}-\text{z-score}_{\text{GINI}}-\text{z-score}_{\text{EL\_IMP}})/4\end{gathered}$$

$$\begin{gathered}\text{GOVERNANCE SUBINDEX} = \\ (\text{z-score}_{\text{POL\_STAB\_INDEX}}+\text{z-score}_{\text{MIL\_SPEND\_pGDP}}+\text{z-score}_{\text{CPI}})/3\end{gathered}$$

$$\begin{gathered}\text{MANMADE THREATS SUBINDEX} = \\ (\text{z-score}_{\text{COASTLINE}}+\text{z-score}_{\text{GLO\_CYBSEC\_INDEX}}-\text{z-score}_{\text{FRAG\_STATE\_INDEX}}- \\ \text{z-score}_{\text{EX\_INT\_INDEX}}-\text{z-score}_{\text{SEC\_THREATS\_INDEX}})/5\end{gathered}$$

$$\text{NATURAL ENVIRONMENT SUBINDEX} = (\text{z-score}_{PC/CO2}+\text{z-score}_{AGR\_LAND}+\text{z-score}_{FOR\_LAND}+\text{z-score}_{ENV\_SUST\_INDEX}-\text{z-score}_{CARB\_INT})/5$$

The calculation of the final energy security index is done according to the following formula:

$$\text{Energy Security Index} = (\text{PHYSICAL AVAILABILITY SUBINDEX}\times 8.8+\text{TECHNOLOGY DEVELOPMENT SUBINDEX}\times 8+\text{ECONOMIC AFFORDABILITY SUBINDEX}\times 8+\text{SOCIAL ACCESSIBILITY SUBINDEX}\times 6.8+\text{GOVERNANCE SUBINDEX}\times 8+\text{NATURAL ENVIRONMENT SUBINDEX}\times 5.8+\text{MANMADE THREATS SUBINDEX}\times 6.8)/(8.8+8+8+6.8+8+5.8+6.8)$$

Table 4.2 shows the values of the subindexes and the values of the overall energy security index for each country. The countries are ranked in decreasing values of the energy security index. Negative numbers indicate that the country is below the average of the 35 countries.

Table 4.2. Energy security index and country rankings for 2020

Ranking	*Countries*	*Physical availability subindex*	*Technology development subindex*	*Economic affordability subindex*	*Social accessibility subindex*	*Governance subindex*	*Manmade threats subindex*	*Natural environment subindex*	*Energy security index*
1	Norway	0.570	1.041	1.872	1.426	1.968	1.664	0.330	1.283
2	Sweden	0.607	1.849	0.881	0.919	1.032	1.005	0.916	1.031
3	USA	2.537	1.266	1.068	-1.863	1.141	0.596	0.738	0.877
4	Iceland	-0.180	2.646	1.192	1.778	0.060	0.662	-0.421	0.838
5	Finland	-0.191	1.065	0.962	0.682	1.315	0.888	1.218	0.820
6	Luxembourg	-0.350	-0.569	2.346	0.734	0.618	0.936	2.402	0.793
7	Switzerland	0.452	1.323	0.819	0.190	0.971	0.452	0.688	0.713
8	Denmark	-0.079	1.288	-0.972	0.882	1.264	1.610	0.570	0.617
9	France	1.164	0.264	0.290	0.146	0.162	0.593	0.852	0.497
10	Austria	0.064	0.920	-0.062	0.270	0.214	0.494	1.210	0.409
11	United Kingdom	-0.236	0.585	0.141	0.036	0.914	0.783	0.352	0.357
12	Germany	1.089	0.643	-0.808	-0.504	0.572	0.927	0.384	0.344
13	Ireland	-0.877	-0.264	1.059	1.169	-0.324	0.633	0.232	0.185
14	Netherlands	-0.556	0.270	-0.393	0.669	0.957	0.830	-0.424	0.182
15	Estonia	-0.839	0.255	0.354	0.500	1.211	0.653	-0.959	0.181
16	Portugal	-0.540	-0.165	-0.059	0.132	0.577	1.002	-0.120	0.098
17	Belgium	-0.296	0.143	-0.674	0.656	-0.060	0.390	0.389	0.039
18	Spain	-0.137	-0.396	-0.004	-0.037	-0.538	0.480	0.472	-0.057
19	Slovakia	-0.185	-0.991	0.348	0.600	-0.381	-0.087	0.510	-0.065
20	Slovenia	-0.366	-0.327	-0.261	1.086	-0.542	-0.212	0.373	-0.079
21	Latvia	-0.572	-0.116	-0.115	-0.051	0.030	-0.074	0.074	-0.135
22	Czech Republic	-0.314	-0.478	-0.316	0.749	-0.320	-0.960	0.318	-0.216
23	Lithuania	-0.600	-0.525	-0.856	-0.289	0.622	-0.305	0.362	-0.255

Ranking	*Countries*	*Physical availability subindex*	*Technology development subindex*	*Economic affordability subindex*	*Social accessibility subindex*	*Governance subindex*	*Manmade threats subindex*	*Natural environment subindex*	*Energy security index*
24	Italy	-0.602	-0.239	0.198	-0.955	-0.803	-0.097	-0.002	-0.368
25	China	3.359	0.950	-1.310	-2.18	-1.998	-1.140	-1.304	-0.372
26	Hungary	-0.498	-0.717	-0.195	-0.225	-0.415	-0.846	-0.122	-0.440
27	Poland	-1.002	-1.168	0.587	-0.322	0.082	-0.303	-1.235	-0.464
28	Greece	-0.706	-1.061	-0.427	0.099	-0.238	-0.613	-0.237	-0.477
29	Romania	-0.459	-1.039	0.392	-0.568	-0.656	-1.297	0.106	-0.508
30	Croatia	-0.601	-0.587	-1.360	0.198	-0.643	-0.221	-0.428	-0.549
31	Russian Federation	1.566	-1.395	-2.411	-1.340	-0.907	-1.633	-0.143	-0.861
32	Cyprus	-1.315	-1.052	-1.007	0.614	-0.342	-1.249	-2.451	-0.945
33	India	1.335	-1.133	-0.524	-2.065	-1.779	-1.730	-2.814	-1.108
34	Turkey	-0.732	-1.129	0.990	-1.772	-2.562	-1.650	-1.427	-1.142
35	Bulgaria	-0.512	-1.158	-1.748	-1.367	-1.201	-2.181	-0.410	-1.223

The values of the dimensional subindexes, the overall energy security index, and the corresponding country rankings are discussed in the next section.

4.3. Analysis of findings

The energy security index values for each country based on 2020 data are now discussed. Given the complex and multifaceted nature of energy security, to be able to compare the energy security of different countries meaningfully, various factors reflected in the subindex values will be considered.

4.3.1. Physical availability

Country rankings for the physical availability subindex are shown in Figure 4.2.

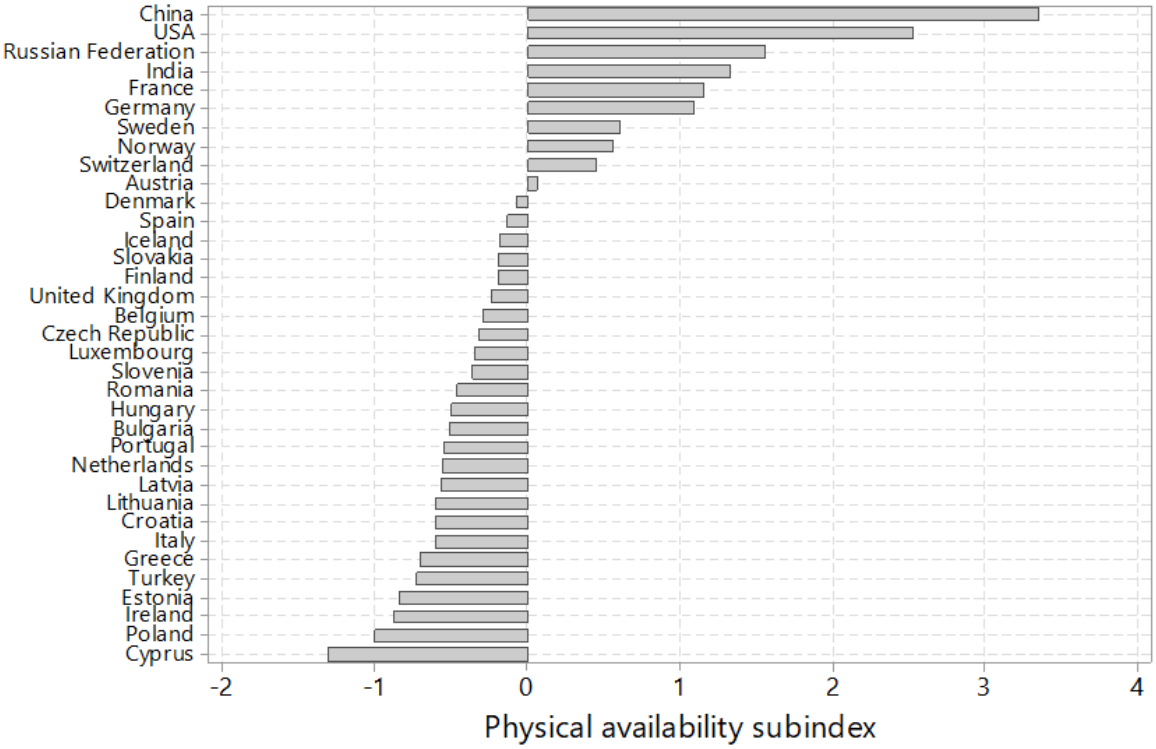

Figure 4.2. Physical availability subindex 2020 per country

China, the US, Russia, India and France are the countries with the highest rankings in the physical availability category. These countries have achieved high scores in electricity generation in TWh, total energy production in quadrillion BTUs, and oil reserves in billion barrels. Additionally, they have significant electricity exports in TWh and a high level of RES electricity generation in TWh. These factors indicate that these countries have a strong physical availability of energy resources and are able to meet their energy demand.

In contrast, the lowest scores in the physical availability category characterize Turkey, Estonia, Ireland, Poland, and Cyprus. These countries have struggled with limited domestic energy resources, leading to lower energy production and reliance on energy imports. As a result, they have a lower ranking in this category.

4.3.2. Technology development

Country rankings for the technology development subindex are shown in Figure 4.3.

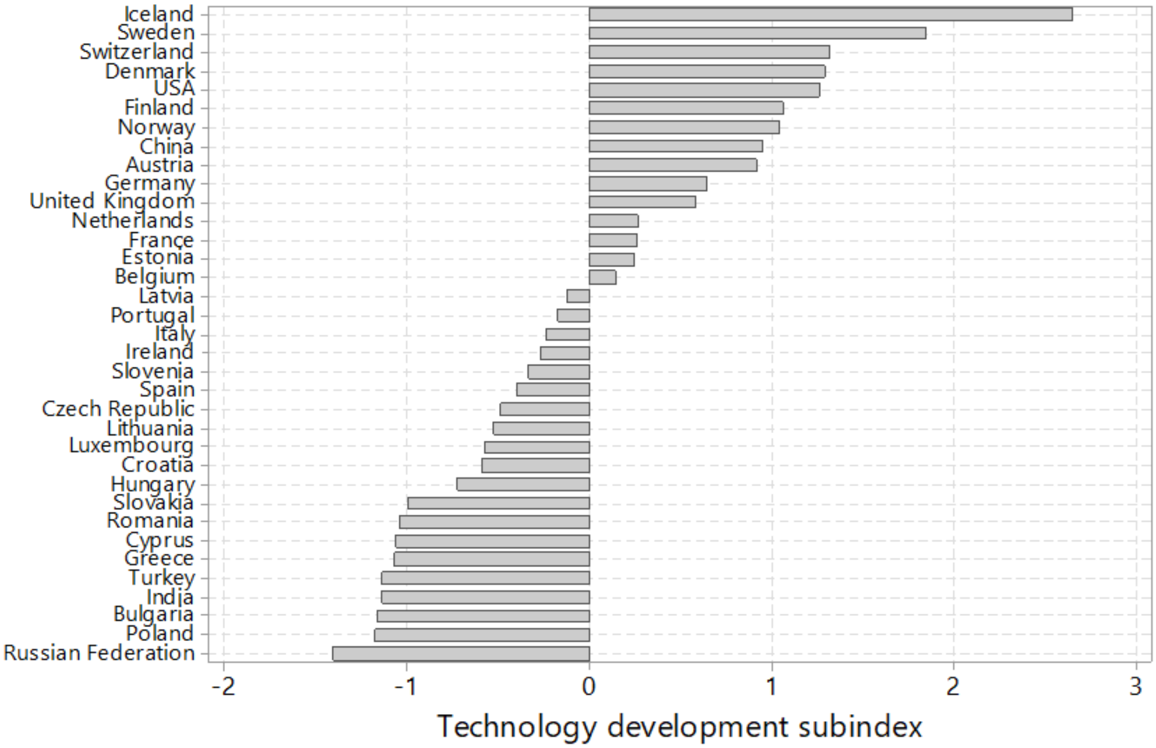

Figure 4.3. Technology development subindex 2020 per country

Iceland, Sweden, Switzerland, Denmark, and the US are among the countries with the highest rankings in the technology development category. These countries have high scores in the Innovations Index (indicating their capacity for innovation), their RES share in the energy mix, and Energy Transition Index, which measure their commitment to the sustainable energy transition. Additionally, they have high expenditures in research and development as a percentage of their GDP and a significant electricity generation capacity.

In contrast, Turkey, India, Bulgaria, Poland, and Russia have the lowest scores in the technology development category. These countries have struggled to make the necessary investments in research and development and transition to RES, negatively impacting their ranking in this category.

4.3.3. Economic affordability

Country rankings for the economic affordability subindex are shown in Figure 4.4.

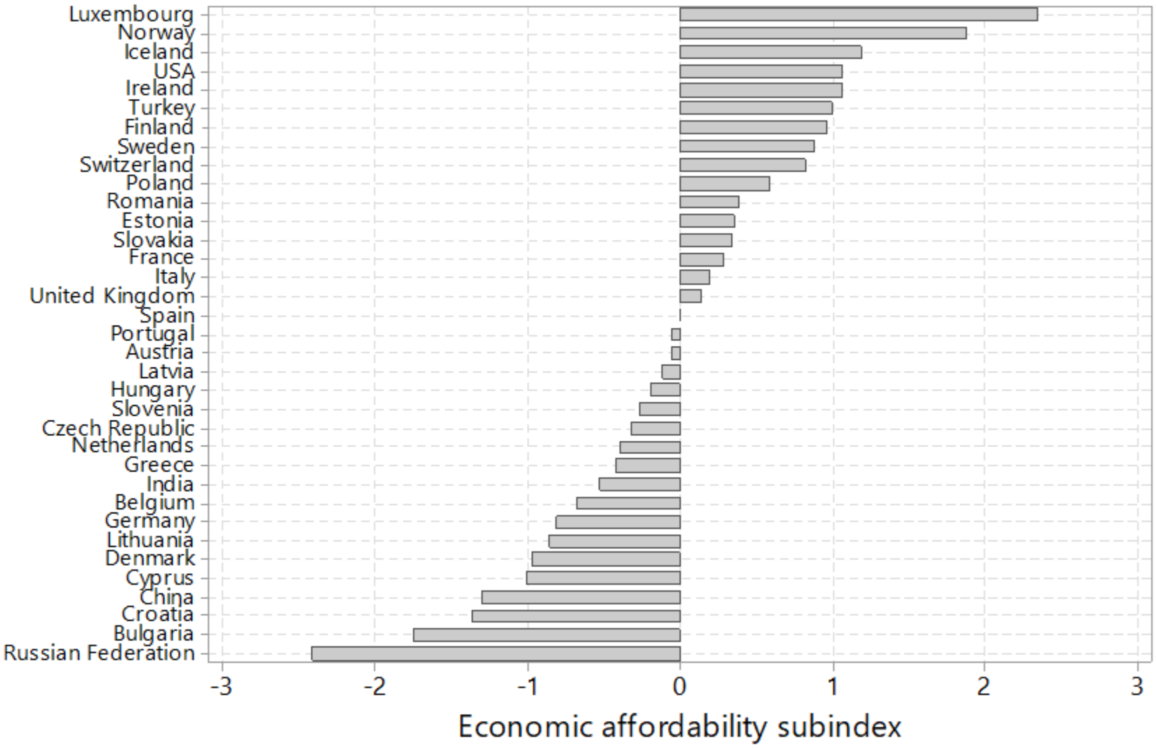

Figure 4.4. Economic affordability subindex 2020 per country

Luxembourg, Norway, Iceland, the US, and Ireland are among the countries with the highest rankings in the economic affordability category. These countries have achieved high scores in GDP per capita (indicating their strong economic performance), low energy intensity, and the price of 1 kWh of energy. In these countries, energy is affordable for the average citizen, and they have made efforts to reduce their energy consumption through efficiency measures.

In contrast, the lowest scores in the economic affordability category are found for Cyprus, China, Croatia, Bulgaria, and Russia. These countries have struggled with high energy prices and have yet to make the necessary investments in energy efficiency and renewable energy, negatively impacting their ranking in this category.

4.3.4. Social accessibility

Country rankings for the social accessibility subindex are shown in Figure 4.5.

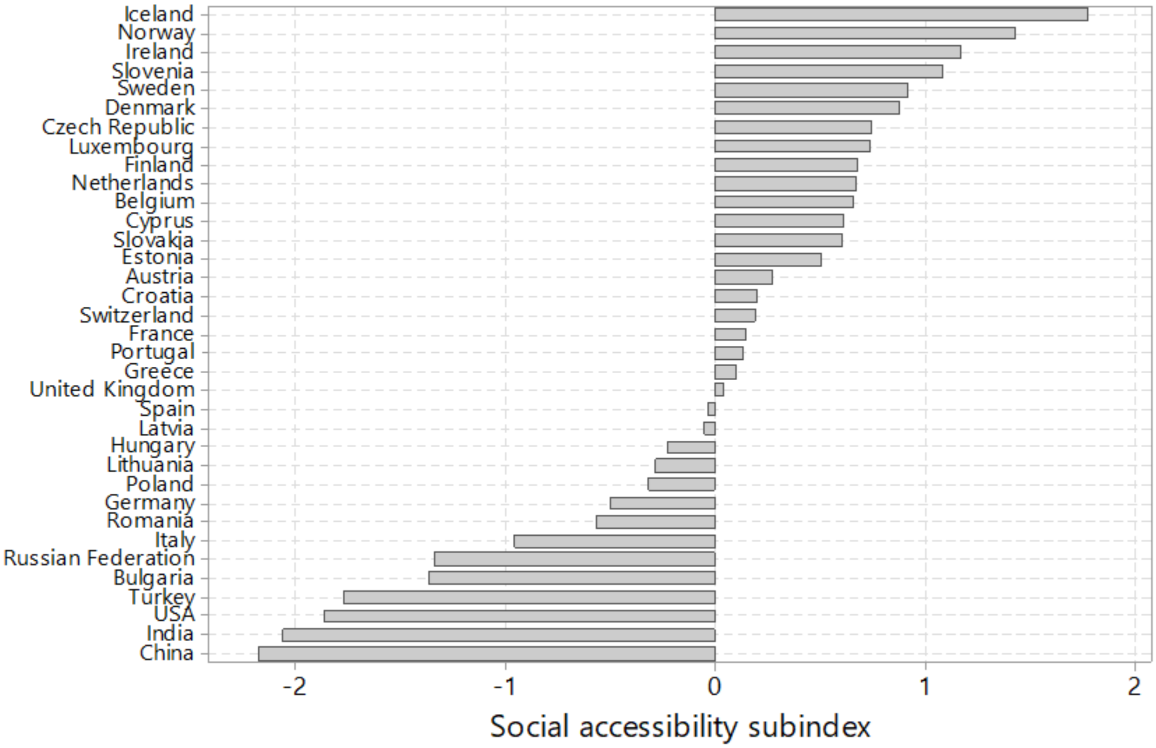

Figure 4.5. Social accessibility subindex 2020 per country

Iceland, Norway, Ireland, Slovenia, and Sweden are among the countries with the highest rankings in the social accessibility category. These countries have achieved high scores in energy equity, which means that they have made efforts to ensure that all members of their society have access to affordable and reliable energy. These countries have strong democracies, which can help ensure that energy policy is developed and implemented transparently and inclusively. They also have low scores in the GINI index, indicating an equal distribution of income, which can contribute to greater social accessibility of energy. Moreover, they have low electricity imports in TWh, meaning they are less dependent on energy imports.

In contrast, the lowest scores in the social accessibility category are found for Bulgaria, Turkey, the US, India, and China. These countries have struggled on distinct occasions with energy poverty, lack of access to reliable and affordable energy for some of their citizens, and a less democratic system of governance in some cases, leading to a lower ranking in this category.

4.3.5. Governance

Country rankings for the governance subindex are shown in Figure 4.6.

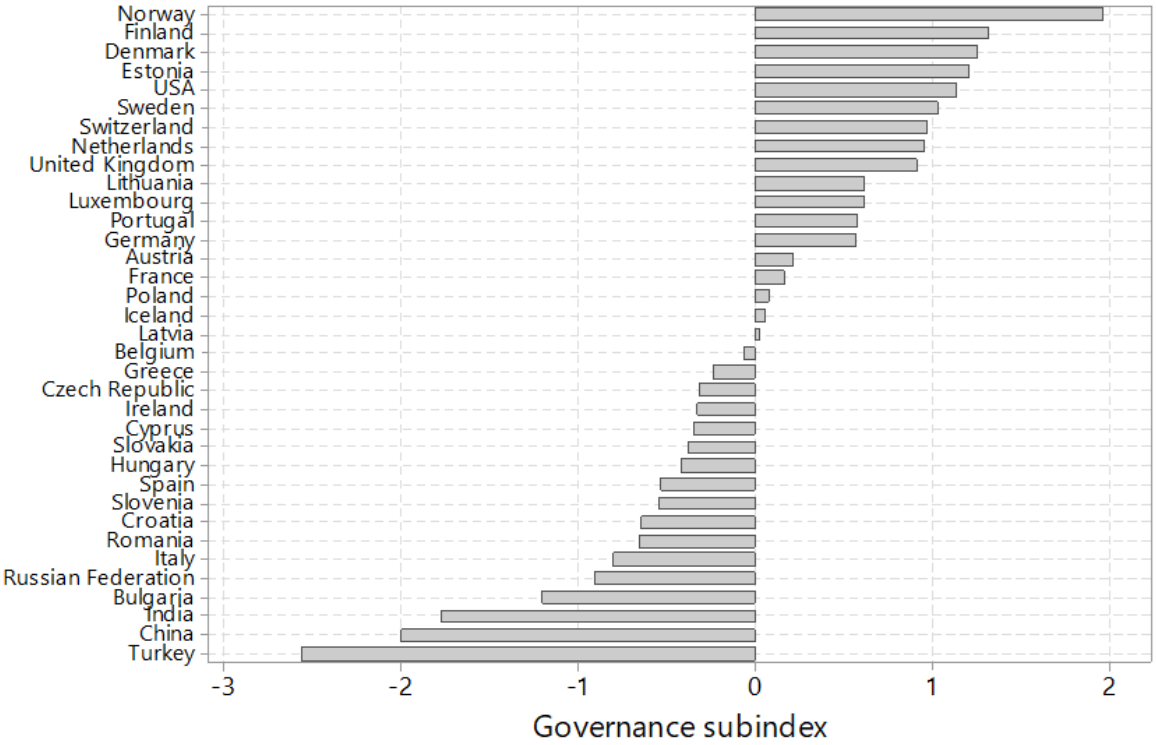

Figure 4.6. Governance subindex 2020 per country

Norway, Finland, Denmark, Estonia, and the US are among the countries with the highest rankings in the governance category. These countries have achieved high scores in political stability, which can help provide a predictable environment for energy policy development and implementation. Moreover, they have high military spending as a percentage of GDP, indicating a stable and secure environment for energy infrastructure development and maintenance. In addition, they have high scores in the corruption perception index, which means a lower level of perceived corruption that can contribute to more transparent and accountable governance in energy policy.

Conversely, Russia, Bulgaria, India, China, and Turkey have the lowest scores in the governance category. These countries have struggled occasionally with political instability, authoritarian regimes, and less transparent governance systems, leading to a lower ranking in this category.

4.3.6. Manmade threats

Country rankings for the manmade threats subindex are shown in Figure 4.7.

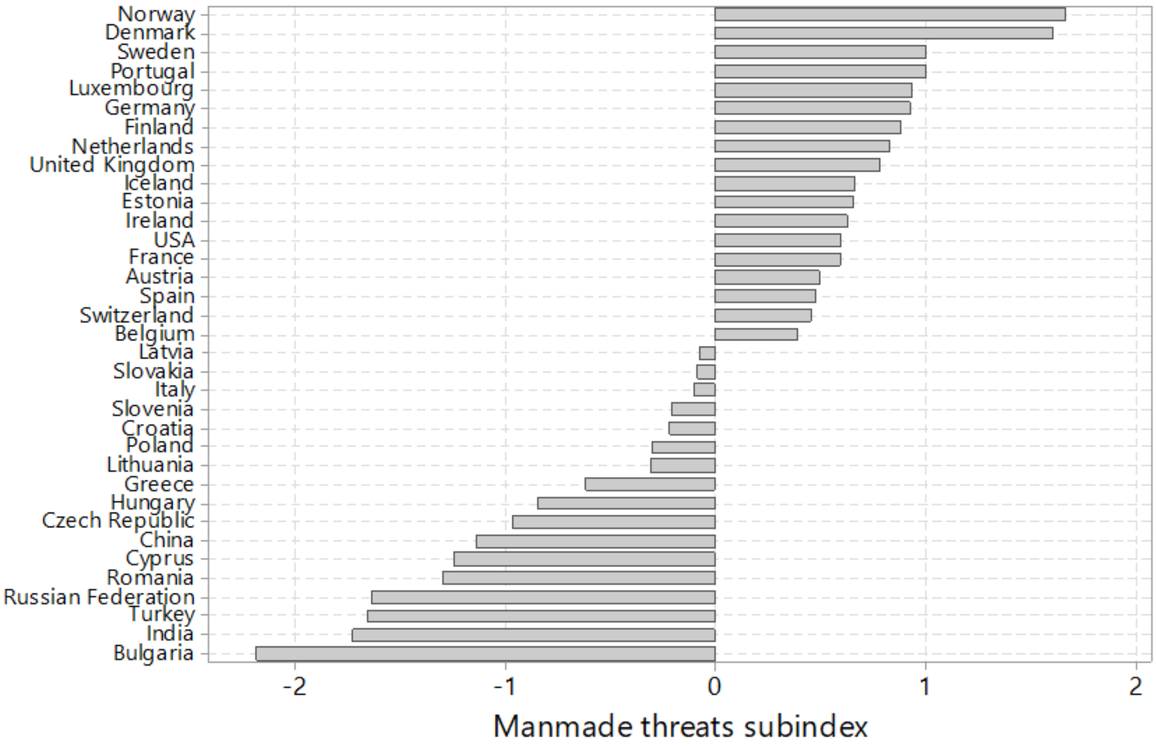

Figure 4.7. Manmade threats subindex 2020 per country

Iceland, Denmark, Norway, Slovenia, and Ireland have the highest rankings in the manmade threats category. These countries have achieved lower scores in the security threats index, external interventions index, and fragile state index, indicating a lower likelihood of being affected by manmade threats. Moreover, they have higher cybersecurity index scores, indicating their ability to protect their information infrastructure from cyber attacks. Additionally, these countries have a higher percentage of coastline, which may increase their resilience against other manmade threats.

Conversely, the lowest scores in the manmade threats category are found for Romania, Russia, Turkey, India and Bulgaria. These countries have struggled with higher scores in the security threats index, external intervention index, and fragile state index, indicating a higher likelihood of being affected by manmade threats. They also have lower scores in the cybersecurity index and a lower percentage of coastline, which can increase their vulnerability to some manmade threats.

4.3.7. Environment

Country rankings for the environment subindex are shown in Figure 4.8.

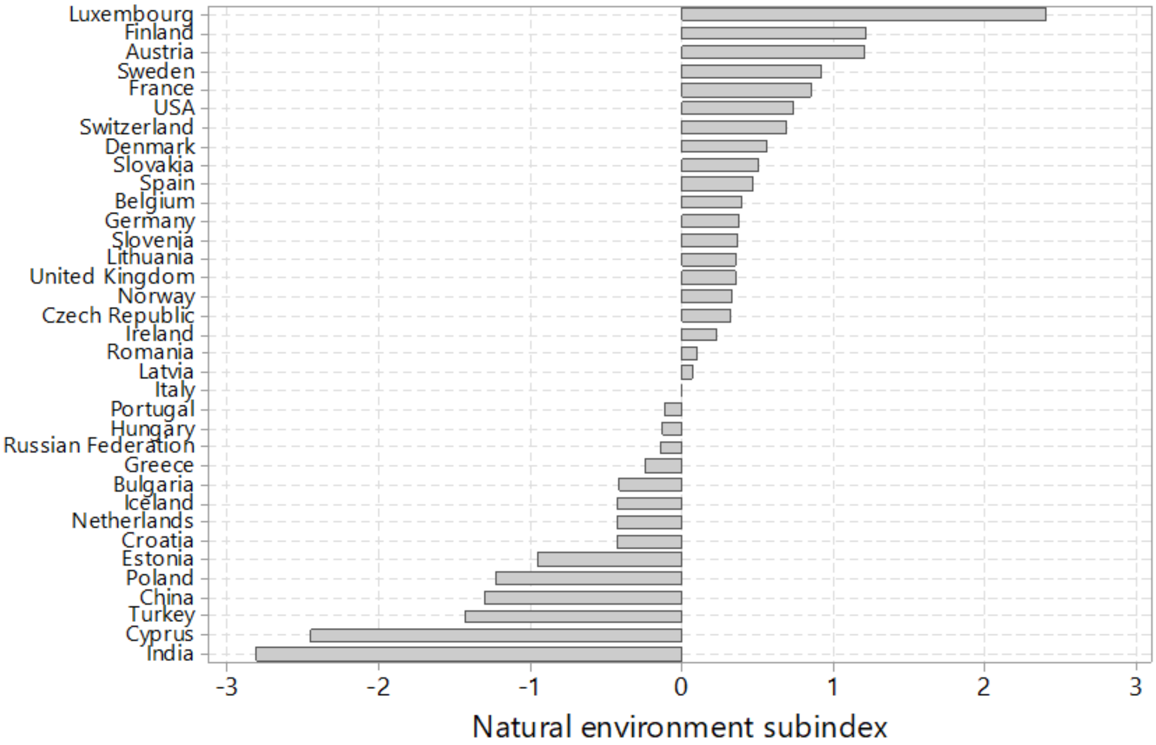

Figure 4.8. Natural environment subindex 2020 per country

Luxembourg, Finland, Austria, Sweden, and France are among the countries with the highest rankings in the environment category. These countries have achieved low per capita CO_2 emissions, which indicate a lower carbon footprint per person. Moreover, they have low carbon intensity in gCO_2 equivalent, which indicates a lower carbon footprint per unit of energy consumed. Additionally, these countries have higher percentages of forest and agricultural land share, which can help mitigate the effects of climate change by acting as carbon sinks. Furthermore, they score higher on the environmental sustainability index, which considers various environmental indicators.The measurement of fossil emissions pertains to the amount of carbon dioxide (CO_2) released from the combustion of fossil fuels and from industrial procedures like the production of steel and cement. Fossil CO_2 emissions comprise those originating from coal, oil, gas, flaring, cement, steel, and other industrial operations. It's worth noting that fossil emissions don't encompass land use changes, deforestation, soils, or vegetation (Our World in Data).

Conversely, Poland, China, Turkey, Cyprus, and India have the lowest scores in the environment category. These countries have struggled with high per capita CO_2 emissions, high carbon intensity, and lower percentages of forest and agricultural land share, leading to a lower ranking in this category.

4.3.8. Energy security rankings

Country rankings for the overall energy security index are shown in Figure 4.9.

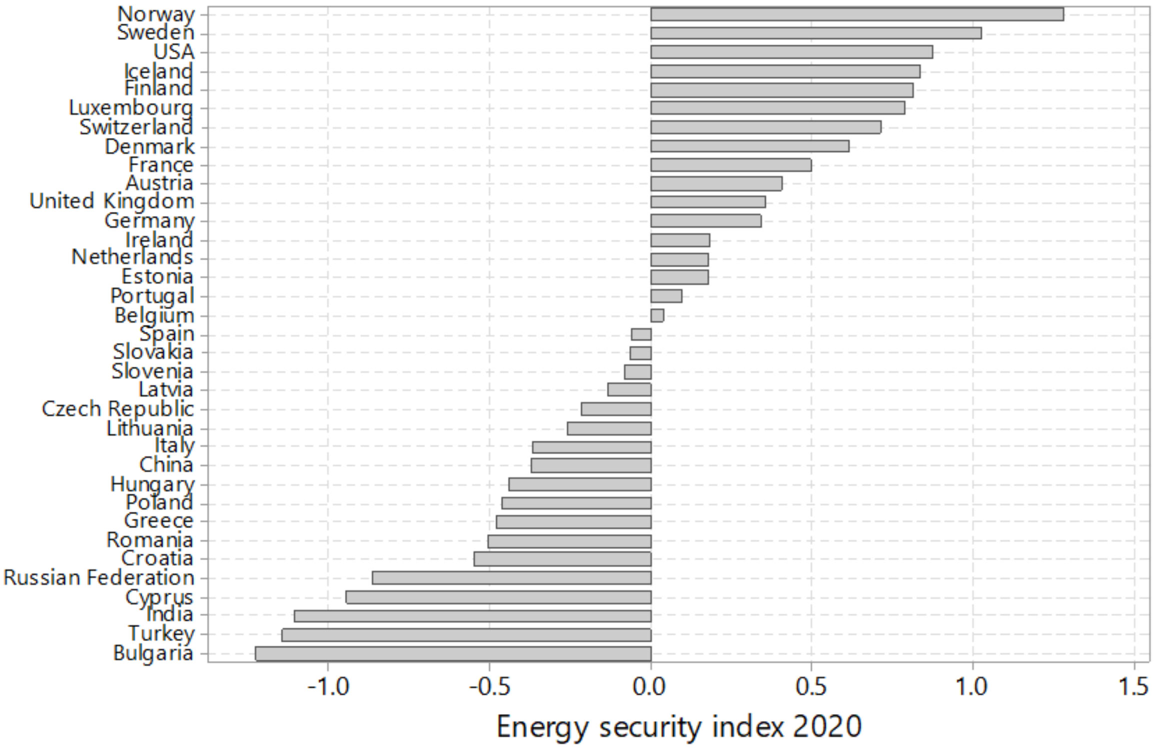

Figure 4.9. Energy security index 2020 per country

The developed energy security index measures a country's energy security based on its performance across the previous seven dimensions: physical availability, technology development, economic affordability, social accessibility, government, manmade threats, and the environment. Countries like Norway, Sweden, the US, Iceland, and Finland ranked high in the energy security index due to high scores in most of the dimensions. For instance, they have high electricity generation capacity, a high share of RES in their energy mix, high GDP per capita, low energy intensity and electricity prices, high scores in political stability and democracy, low carbon emissions, and a low incidence of manmade threats.

Conversely, Russia, Cyprus, Turkey, India, and Bulgaria have the lowest rankings in the index due to poor performance across these subindexes.

4.4. Geothermal potential

Prior to exploring the estimation of reserves and geothermal potential, it would be advantageous to comprehend how the oil and gas industry manages reserves. In the energy sector, the term reserve refers to the estimated amount of oil or gas that can be produced using current technology and at current energy prices. While the resource base is typically larger than the reserve, the estimated size of the reserve may increase as extraction technology improves or energy prices rise. As an illustration, in deep sedimentary rock, some of the methane is dissolved in the water present in the reservoir rock's pores, which may be regarded as part of the natural gas resource base. If all the methane within subsurface rock were quantified, a significant amount of energy would be available in this resource. However, dissolved methane is typically not included in natural gas reserve estimates because it is too dilute and/or too costly to extract. If technological advancements make extracting dissolved methane from geothermal fluids more feasible, the methane present in these fluids could be included in reserve estimates. This idea is similar to methane trapped in gas hydrates in permafrost and marine sediments or to uranium dissolved in seawater and considered part of the uranium resource base. The same principle applies in cases where high capillary pore pressure in a sedimentary rock affects the recovery factor of oil in a given reservoir, as Hemmat Esfe, Esfandeh, and Hosseinizadeh (2020) point out. Residual oil that cannot be retrieved is accounted for in the resource estimation, nevertheless it does not constitute a recoverable reserve.

According to rules set by the U.S. Securities and Exchange Commission, the oil and gas industry classifies reserve estimates as proven, probable, and possible. Proven reserves are commercially recoverable, whereas probable reserves are likely to be recoverable with a probability of at least 50%. Potential reserves are less likely to be recoverable, with a maximum probability of 10%, and are often determined through statistical analysis. Possible reserves may have favorable geology and geophysics but may not be commercially viable or require the development of new technologies. Nevertheless, the industry’s production history provides confidence in these estimates.

A hydrothermal geothermal system is a common and effective method of harnessing geothermal energy. It utilizes the natural circulation of water deep within the Earth's crust to extract heat. Typically found in regions with active volcanism or tectonic activity, these systems consist of reservoirs of hot water or steam within permeable rock formations. As water seeps into the Earth, it becomes heated by the rocks' high temperatures and rises to the surface as hot water or steam. To tap into this energy source, wells are drilled into the geothermal reservoirs, allowing the hot fluid to be brought to the surface. This steam can then be used to drive turbines and generate electricity in a geothermal power plant. Hydrothermal geothermal systems are renewable, sustainable, and provide consistent baseload power, making them valuable for meeting energy demands worldwide, as Wang et al. (2022) explain.Hydrothermal geothermal resources have been drilled and produced in the past, providing information on proven, probable, and possible reserves. However, speculation still exists since hydrothermal fields have yet to be depleted of heat to uneconomical levels. Assessing geothermal resources is an essential step in determining the feasibility of a geothermal project. However, finding a balance between a comprehensive and a limited resource assessment can be challenging, particularly in the initial phases of a project when information is limited.

At present, the most effective method for assessing geothermal projects before development is the volumetric approach. At the same time, numerical reservoir simulation is the most efficient tool for managing and producing geothermal resources and predicting their future behavior and capacity. According to Ciriaco, Zarrouk, and Zakeri (2020), relying on a single method to determine geothermal potential is generally inadequate because each method has limitations. To address these limitations, combining two or more methods is often necessary. Using other methods simultaneously is advisable, particularly for understanding short-term reservoir processes resulting from fluid extraction. Methods for estimating geothermal potential include the surface heat flux, planar fracture, magmatic heat budget, total well flow, mass-in-place, power density, delineating reservoir area, decline analysis, lumped parameter, and volumetric methods (Ciriaco, Zarrouk & Zakeri, 2020). Each method has its own limitations and advantages, useful for different stages of exploration and with varying levels of available data.

Reservoir simulation is a valuable tool for managing geothermal reservoirs and predicting their future capacity. It can be used at all stages of development, including the early stages. Reservoir simulation involves building a mathematical model of the reservoir based on geological and geophysical data. Full-scale numerical models are difficult to build and calibrate, but they provide consistency checks with conceptual models and aid in exploration and monitoring programs. Such models are then used to simulate the behavior of the reservoir under various conditions, such as changes in production rates or injection rates. By analyzing the results of these simulations, reservoir engineers can gain insights into the behavior of the reservoir and make more informed decisions about how to manage it. For example, reservoir simulation can help to optimize the production strategy, estimate the ultimate recovery of the reservoir, and identify areas of the reservoir that may be underutilized. Therefore, reservoir simulation is crucial for optimizing production and injection strategies, designing new wells, and mitigating environmental and economic risks associated with reservoir depletion and production. However, it should be noted that when using simulation tools for optimization, uncertainty quantification, and data assimilation, the computational demands can be significant, necessitating thousands of simulation runs. This high computational cost can sometimes make using such simulation tools impractical or unfeasible (Jin, Liu, & Durlofsky, 2020).

Geothermal resources can be available on the surface or underground. However, adequately high temperature, flow rate, and economic value must be considered. Given those multiple scientific specializations need to cooperate in assessing geothermal resources, no universal calculation or statistical model exists for assessing geothermal potential. Even when the same classification model is adopted, the uncertainty of parameters such as reservoir thickness, temperature, porosity, and heat recovery rate, often derived from experience or Monte Carlo simulations, can lead to significant differences in the estimation of available resources.

The utilization of geothermal energy is mainly determined by its temperature, which can be classified as high, medium, or low. Electricity production is ideal for medium to high-temperature resources, with a minimum temperature of 150 to 180°C required for commercial-scale electricity generation. However, existing technologies can generate electricity from temperatures as low as 70°C in small-scale applications (IRENA, 2023). Electricity generation from geothermal energy has been predominantly limited to regions with naturally occurring high-temperature geothermal fluids, typically between 100°C and 300°C, either as wet steam or water-dominated fluids. In this case, the targeted geothermal fields are distinguished by naturally occurring high permeability and secondary porosity resulting from geochemical processes in the host rock, which enable sufficient fluid circulation in the reservoir (Deb et al., 2020). However, these types of reservoirs present two significant limitations. Firstly, they are typically located near tectonic boundaries and volcanic zones, which restricts the geographical expansion of geothermal energy beyond these areas. Secondly, such reservoirs can be exploited for a finite period, after which the fluid contained within them is fully extracted. This is similar to oil and gas reserves (Olasolo et al., 2016).

The theoretical potential of EGS refers to the available heat stored underground within rocks. A rock's heat content is determined by various factors, including the temperature at different depths and the specific heat capacity, density, and volume of the rock (Aghahosseini & Breyer, 2020). However, multiple geographic, ecological, legal, and regulatory restrictions render the total sum of theoretical potential impossible to reach. On the other hand, technical potential refers to the fraction of theoretical potential that can be extracted given the current technology and the aforementioned restrictions. Land availability plays a key role in the assessment of technical potential. It should be noted that some constraints, such as drilling costs and technology, may change over time. Enhancement of the drilling technology is the key to minimization of the levelized cost of energy (LCOE) for geothermal development, which represents a key factor in the exploitation of the available technical potential. However, it can be assumed that continuous technological research and development of geothermal energy will render cost-effective, safe, and environmentally friendly the exploitation of geothermal potential in these depths in the future, impacting the energy security of states and regions.

Unlike mining, geothermal heat extraction allows the extracted heat to be replenished over time, albeit slowly. The duration required for geothermal resources to regenerate depends on various factors, including the characteristics of the resource, the type and size of the production system, and the extraction rate. Generally, lower extraction rates can sustain a relatively consistent production throughout the lifespan of EGS systems. Experts suggest that geothermal energy can be deemed a sustainable resource as long as a small portion, such as less than 10% of the total geothermal technical potential, is utilized. This fraction of the technical potential that can be utilized under this consideration and constraint is the sustainable geothermal potential (Aghahosseini & Breyer, 2020).

Determining the maximum potential of geothermal energy worldwide becomes necessary in the era of the energy transition. Geothermal energy exists in abundance both on the surface and underground. However, the geothermal resources available are defined by the quality, quantity, and reasonable prospects of economic extraction (Xia & Zhang, 2019). Shallow geothermal energy for direct use and conventional geothermal energy for direct use and electricity generation were the two main categories of geothermal energy being adopted worldwide. Geothermal energy's classification has been altered by technological innovation. Eventually, it has been divided into direct use, district heating systems, electricity generation via geothermal power plants, and geothermal heat pumps (Melikoglu, 2017). For a very long time, hydrothermal, the traditional geothermal power technology, has been commercialized for electricity generation. EGS is a new geothermal technology developed only in a few locations.

Modern geothermal power plants can yield capacity factors up to 95%, increasing the geothermal potential dramatically in combination with EGS. Precise geologic information, such as crustal stress, is integral for choosing a suitable drilling strategy and specifying drilling sites. Geothermal heat can be extracted from the earth at varying rates. However, to ensure sustainable use of this energy source, it is necessary to replace the heat removed from the resource on a similar time scale (Chamorro et al., 2013)). The operation of a geothermal power plant for 30 years can result in a temperature decrease of up to 10°C at depths of 10 km, altering the rock's properties. This process is not strictly considered a renewable or sustainable production scheme but rather a form of heat mining (Chamorro et al., 2013).

Depending on their unique characteristics, various geothermal technologies can be employed in geothermal reservoirs, which play a significant role in determining the development costs. The overall life cycle costs of a geothermal project decrease as the temperature of the source rock increases due to an inverse correlation between the two factors. Technology, however, is one of many factors affecting a geothermal project's cost. According to Xia and Zhang (2019), the operation, maintenance, and transportation costs and the time required for drilling operations can significantly differentiate extraction costs.

Much of the geothermal potential is trapped in low porosity and low permeability areas, known as hot dry rocks (HDR). The geothermal industry has been actively developing techniques to extract energy from HDR systems using EGS. EGS involves drilling deep into the earth's crust to access the hot rocks and injecting water or other fluids at high pressure to create fractures. This allows the water to flow through the fractures, absorb heat from the rocks, and become heated to a high temperature. EGS aim at the exploitation of available hot rock resources with low permeability. For permeability enhancement, pre-existing fractures are propagated, or new ones are created to extract thermal energy through the circulation of geothermal fluids or water. The fluids are then pumped into binary or flash plants on the surface for electricity generation (Chamorro et al., 2013).

EGS techniques have been the main focus of research and development in the geothermal industry over the last few years. Pilot projects aimed at developing EGS are currently in operation in several locations, including the Soultz-sous Forêts and Rittershoffen power plants in France. The development of EGS is currently facing obstacles related to economic and technological limitations in the exploration, drilling, and stimulation phases of geothermal reservoirs. Additionally, the technology for EGS is not yet commercially implemented on a large scale, which limits its potential for wider adoption as a source of renewable energy (Deb et al., 2020).

Geothermal technologies play a crucial role in forecasting geothermal potential worldwide, as each one provides different capabilities. Geothermal energy is generated by the heat stored in the earth's crust, and technologies such as drilling, well stimulation, and power plant design are used to harness this energy. Advances in geothermal exploration and development technologies have made it possible to estimate the approximate global geothermal potential and identify areas with high potential, facilitating the planning and implementation of geothermal projects worldwide.

4.4.1. Forecasting technical and sustainable potential

Having discussed geothermal potential, we turn to forecasting it.

Utilizing just 1% of the total estimated geothermal potential could generate a constant power supply for humanity for 2800 years (Anderson & Rezaie, 2019). Nevertheless, the primary challenge in implementing geothermal technology is identifying suitable locations and extraction techniques. Improved drilling techniques could make it possible to sustainably exploit geothermal potential in areas where geothermal project development is currently not feasible.

The total installed geothermal capacity for 2021 around the world is illustrated in Figure 4.10.

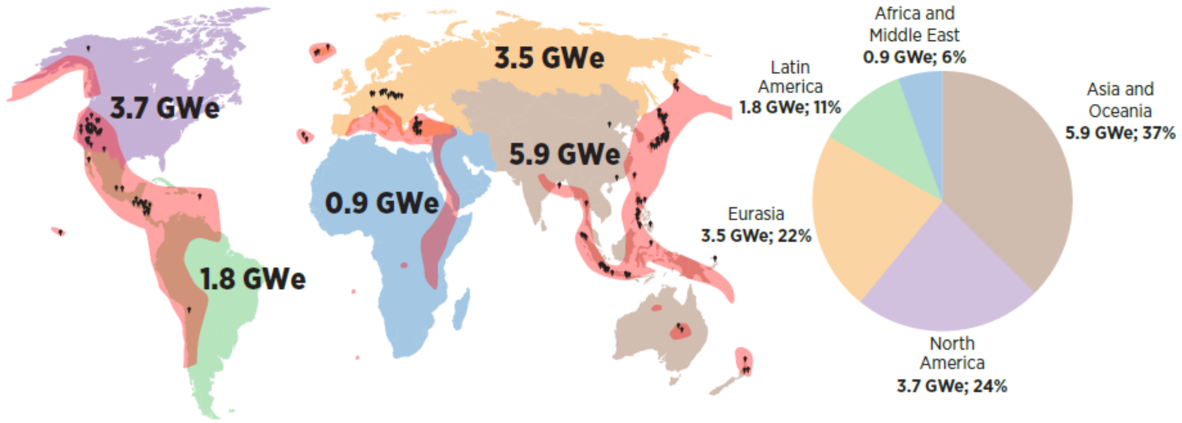

Figure 4.10. Installed geothermal electricity capacity by region in 2021 (IRENA, 2023).

The use of geothermal energy for generating electricity has been growing steadily at a rate of around 3.5% per year, resulting in a total installed capacity of approximately 15.96 gigawatts of electricity (GWe) as of 2021 (IRENA, 2023). This growth was partly due to the oil crises of the 1970s and 1980s, which led to increased research and development of alternative energy sources, including geothermal. Geothermal energy provided countries with a locally available alternative to imported fossil fuels for electricity generation.

Despite this progress, geothermal power makes up only 0.5% of renewable-based installed capacity for electricity generation, heating, and cooling worldwide (IRENA, 2023). Attempts have been made to estimate and map the theoretical and technical potential of geothermal energy worldwide, with the work of Beardsmore et al. (2010) being particularly noteworthy. The installed capacity of geothermal projects worldwide can reach 70 GWe by 2050, as illustrated in Figure 4.11, with a probability of 85% (Lu, 2018).

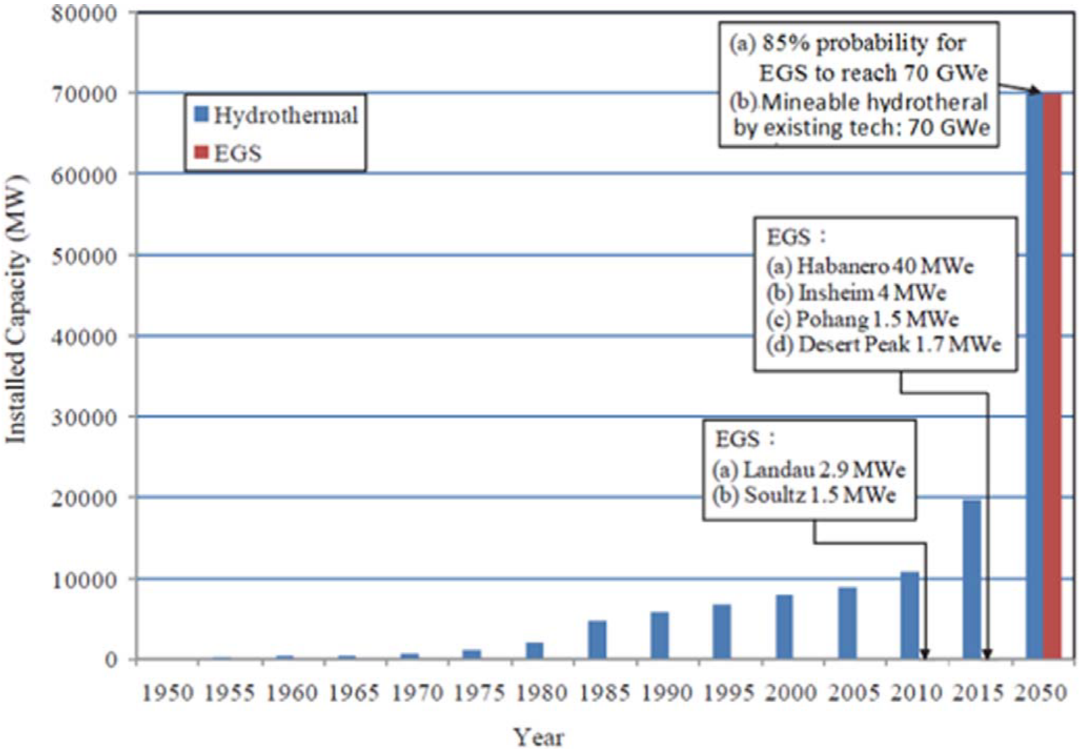

Figure 4.11. Prediction of Installed capacity of EGS worldwide (Lu, 2018)

Another study (Bertani, 2016) proposed that the installation of geothermal power capacity worldwide could reach 140 GW by 2050. If this were to happen, geothermal energy would contribute 8.3% of global electricity generation and serve 17% of the population. Furthermore, 40 nations would generate all their electricity from geothermal sources.

A comparison of the technical and sustainable potential of geothermal energy in Europe was conducted by Chamorro et al. (2013). A depth of 10 km was considered the limit of currently available drilling technology, while temperatures up to 9500 m were calculated. No economic aspects of geothermal development were considered. There was a partially proportional relationship between drilling depth and the percentage of surface area with geothermal temperatures exceeding 150°C, as illustrated in Figures 4.12, 4.13, and 4.14.

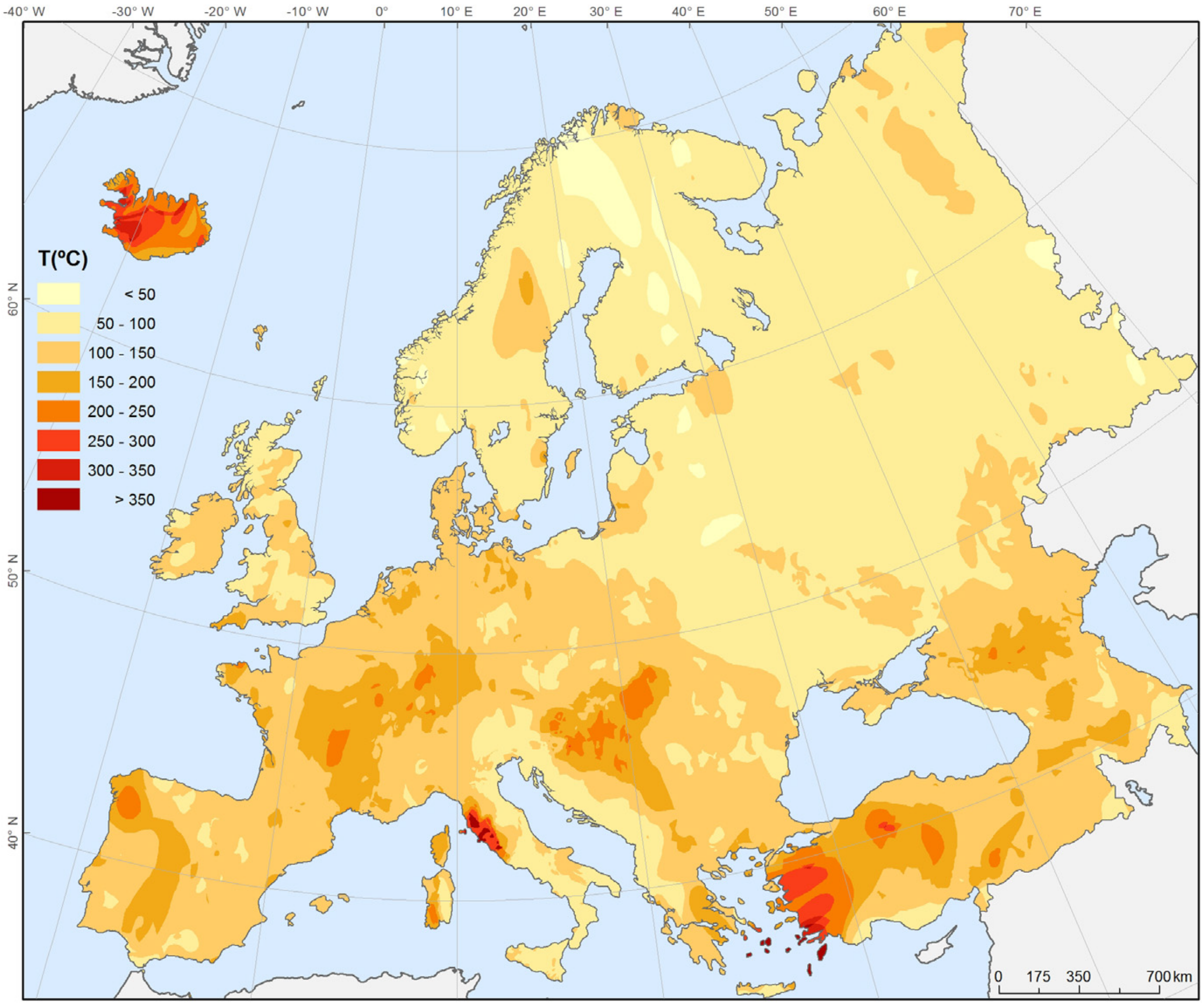

Figure 4.12. Map of calculated temperature at 4500 m depth for Europe (Chamorro et al., 2013)

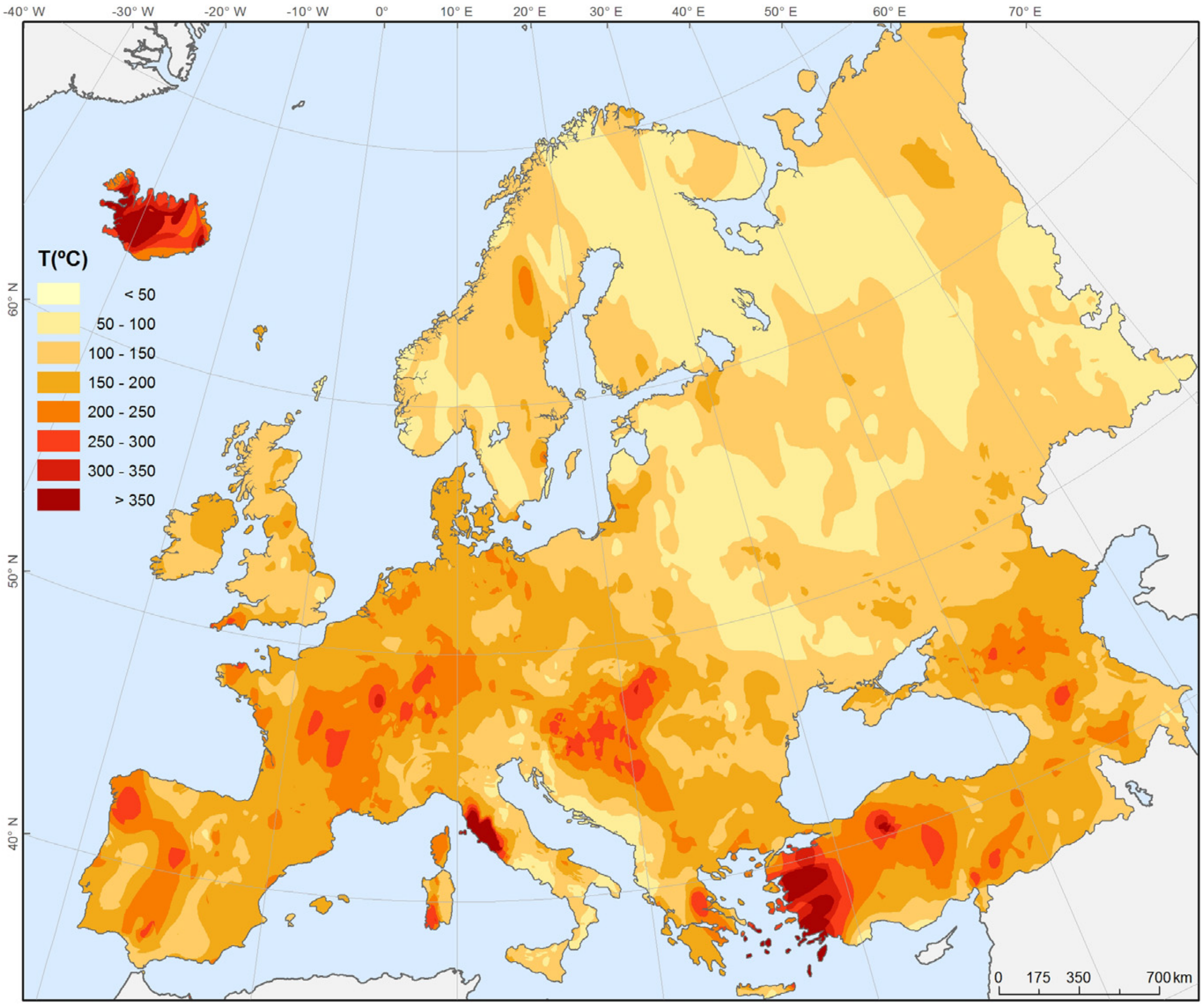

Figure 4.13. Map of calculated temperature at 6500 m depth for Europe (Chamorro et al., 2013)

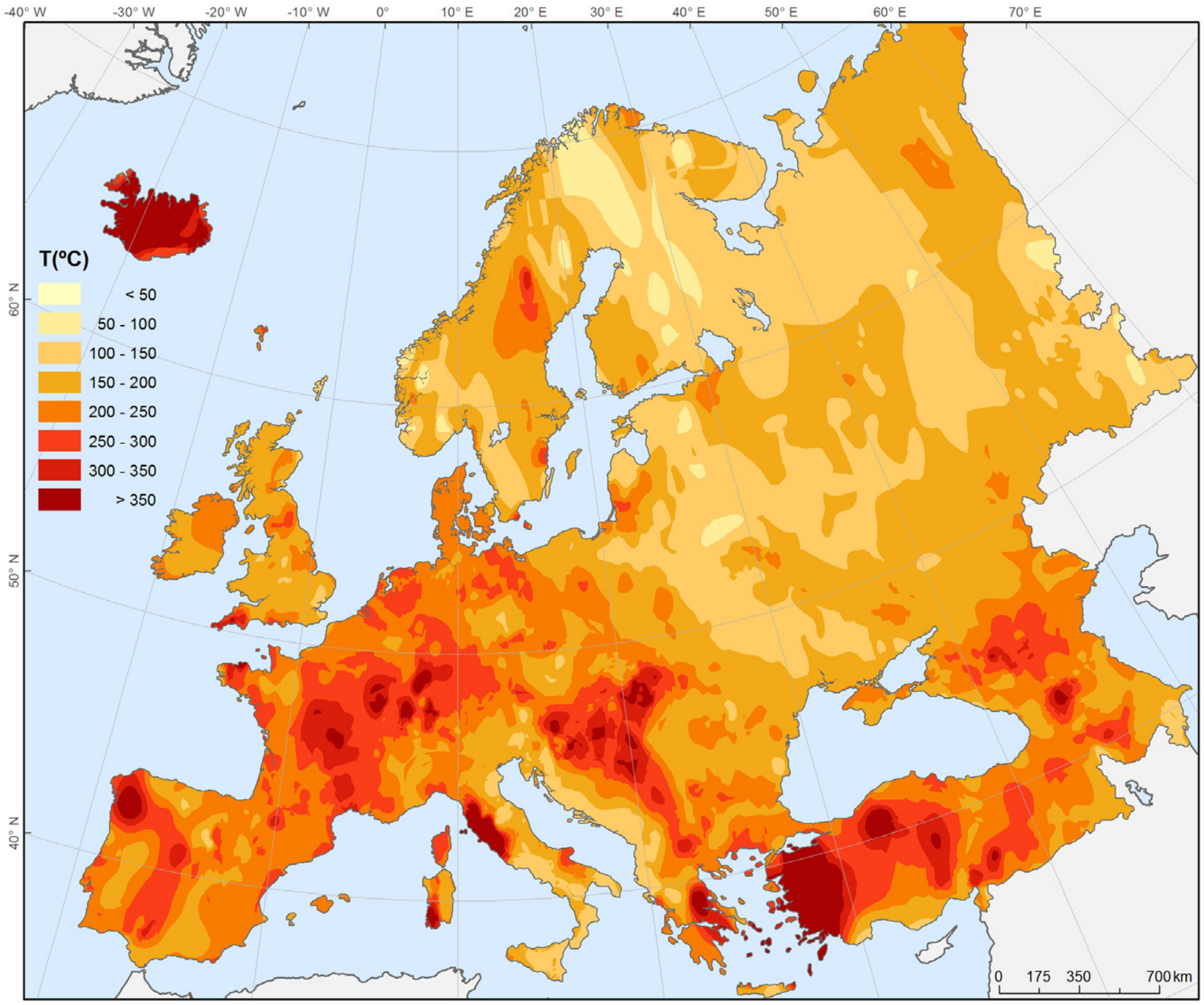

Figure 4.14. Map of calculated temperature at 9500 m depth for Europe (Chamorro et al., 2013)

At depths of 4500 m, 9% of the surface has a temperature higher than 150°C, as illustrated in Figure 4.12. This percentage is 33% and 70% when depths of 6500 m and 9500 m are reached, respectively, as illustrated in Figures 4.13 and 4.14. In other words, when we go to depths of 6.5 km, the percentage of land surface that has geothermal reservoirs with a temperature higher than 150°C increases from 9% to 33%. At depths of 9.5 km, this percentage rises to 70%.

Chamorro et al. (2013) calculated the technical potential at depths of 5 km, for temperatures higher than 150°C, to be 298 GWe, expressed as installed electrical power. The technical potential skyrockets if depths of 10 km are reached, as it climbs up to 6560 GWe. According to the same study, the sustainable potential of EGS is 35 GWe. Given that technical potential is 200 times higher than the sustainable one, this hypothesis has been calculated in rather restrictive terms (Aghahosseini & Breyer, 2020). It is logical to assume that not every rock layer deeper than 3 km can be feasibly or realistically exploited for generating geothermal energy through EGS.

Depending on the degree of ambition in mitigating climate change and the costs of EGS, the worldwide production of geothermal electricity and heat by 2050 could attain 800 to 1300 TWh/yr and 3300 to 3800 TWh/yr respectively (Longa et al., 2020). In a rather pessimistic scenario, geothermal power plants could potentially make up around 4 to 7% of the total electricity generation in Europe by 2050. The economically sustainable potential for Europe was estimated to be 19 GWe in 2020, 22 GWe in 2030, and 522 GWe in 2050 (Limberger et al., 2014).

Another study by Aghahosseini and Breyer (2020) presents a scenario where the global EGS potential is estimated to be around 108 TWe. It is further suggested that around 4600 GWe of EGS capacity can be built at a cost of 50 €/MWh or lower. However, considering various constraints, the provided sustainable potential of EGS can be calculated at approximately 256 GWe by 2050, accounting for just 0.2% of the technical potential globally. This study further claims that Russia has the most significant EGS potential in the world (16%), followed by China (9%) and other countries (such as Brazil, the USA, Canada, and Australia), rendering the expansion of EGS as geopolitically important.

The EGS power capacity technical and sustainable potential projection for selected countries for the period 2020-2050 is illustrated in Table 4.3 (Aghahosseini & Breyer, 2020). The technical potential of each country without the application of economic or water stress constraints is illustrated in the second column. The following columns illustrate the technical and sustainable geothermal potential of each country for 2020, 2030, 2040, and 2050, factoring in economic and water stress constraints.

Table 4.3. EGS technical and sustainable power capacity potentials for 2020-2050, expressed as potential installed electrical power (GW), for each country (Aghahosseini & Breyer, 2020)

Country	*EGS technical potential (GWe) (without constraints)*	*EGS technical potential (GWe) 2020*	*EGS sustainable potential (GWe) 2020*	*EGS technical potential (GWe) 2030*	*EGS sustainable potential (GWe) 2030*	*EGS technical potential (GWe) 2040*	*EGS sustainable potential (GWe) 2040*	*EGS technical potential (GWe) 2050*	*EGS sustainable potential (GWe) 2050*
Global	201403.5	1623,21	6,12	5432,16	18,67	58469,39	141,70	108007,16	255,90
Austria	236.59	38,68	0,08	126,11	0,22	170,24	0,31	181,97	0,33
Belgium	50.26	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Bulgaria	196.48	0,00	0,00	0,00	0,00	81,85	0,17	157,12	0,33
China	20885.01	122,18	0,74	286,51	1,21	5434,49	12,77	9882,39	22,59
Croatia	42.69	0,00	0,00	0,00	0,00	24,06	0,06	42,69	0,11
Cyprus	0.00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Czech Republic	151.46	0,00	0,00	0,00	0,00	57,99	0,12	133,22	0,25
Denmark	93.03	0,00	0,00	0,00	0,00	57,70	0,11	93,03	0,17
Estonia	65.95	0,00	0,00	0,00	0,00	18,21	0,02	35,55	0,03
Finland	40.95	0,00	0,00	0,00	0,00	0,00	0,00	13,93	0,03
France	1186.76	0,00	0,00	0,00	0,00	734,15	1,93	1053,80	2,79
Georgia	124.81	0,00	0,00	0,00	0,00	84,00	0,24	84,00	0,24
Germany	753.72	33,33	0,04	71,61	0,13	441,48	0,86	578,27	1,13
Greece	148.91	0,00	0,00	32,10	0,10	32,10	0,10	32,10	0,10
Hungary	188.45	0,00	0,00	24,27	0,07	170,79	0,48	170,79	0,48
Iceland	325.44	128,33	0,45	311,59	1,02	325,44	1,06	325,44	1,06
India	4881.24	0,00	0,00	41,04	0,11	572,29	1,32	1424,49	3,44
Ireland	120.13	0,00	0,00	0,00	0,00	0,00	0,00	35,00	0,08
Italy	717.43	0,00	0,00	52,84	0,07	307,02	0,54	387,55	0,72
Latvia	94.47	0,00	0,00	0,00	0,00	14,82	0,02	33,41	0,04
Lithuania	64.84	0,00	0,00	0,00	0,00	15,57	0,05	32,30	0,07
Luxembourg	0.00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Country	*EGS technical potential (GWe) (without constraints)*	*EGS technical potential (GWe) 2020*	*EGS sustainable potential (GWe) 2020*	*EGS technical potential (GWe) 2030*	*EGS sustainable potential (GWe) 2030*	*EGS technical potential (GWe) 2040*	*EGS sustainable potential (GWe) 2040*	*EGS technical potential (GWe) 2050*	*EGS sustainable potential (GWe) 2050*
Netherlands	38.04	0,00	0,00	0,00	0,00	38,05	0,07	38,05	0,07
Norway	555.21	0,00	0,00	116,62	0,12	277,70	0,30	393,13	0,50
Poland	572.95	0,00	0,00	0,00	0,00	321,90	0,59	507,63	0,88
Portugal	185.27	0,00	0,00	0,00	0,00	42,63	0,11	83,24	0,19
Romania	447.24	0,00	0,00	0,00	0,00	256,75	0,44	362,09	0,60
Russian Federation	23550.81	0,00	0,00	50,59	0,10	9503,54	15,11	17620,79	27,92
Slovakia	72.74	0,00	0,00	0,00	0,00	72,74	0,16	72,74	0,16
Slovenia	47.54	0,00	0,00	0,00	0,00	27,01	0,07	47,54	0,13
Spain	676.71	0,00	0,00	29,76	0,11	118,01	0,34	271,93	0,63
Sweden	412.47	0,00	0,00	0,00	0,00	70,80	0,09	245,86	0,34
Switzerland	211.27	46,53	0,08	109,96	0,18	211,28	0,39	211,28	0,39
Turkey	1677.26	0,00	0,00	60,78	0,26	364,82	0,84	685,52	1,53
United Kingdom	293.79	0,00	0,00	0,00	0,00	109,31	0,18	164,45	0,29
United States	15401.01	148,46	0,33	337,07	0,97	2943,40	6,41	5774,41	11,95

The calculation of geothermal potential takes into account several constraints. Aghahosseini and Breyer (2020) highlight technical limitations for EGS, with land availability being a significant concern. These limitations can be categorized into four groups, including protected and conservation areas, densely populated areas, large lakes and reservoirs, and areas with high water stress. To determine the restricted regions for geothermal development, areas with high water stress (40-80%), extremely high water stress (>80%), and arid or areas with low water usage were identified based on projected changes in water stress. This is important for EGS projects, as they tend to involve relatively high water withdrawals.

Furthermore, to ensure economic viability, any optimum values for the LCoE that exceed 150 €/MWh are excluded, further reducing the estimated technical potential of EGS. The second column of Table 4.3 illustrates the EGS optimal potential in terms of power capacity (GWe) based on the optimum depth, without any applied constraints. For each country, water stress and economic constraints are taken into account when calculating EGS power capacity technical potential for 2020, 2030, 2040, and 2050 in the respective columns.

Additionally, the sustainable geothermal potential is presented for the respective years, considering the constraint of sustainable geothermal energy production at relevant rates. The sustainable potential refers to the energy that can be extracted at a rate equal to the rate of generation within the same rock volume. To estimate the amount of EGS power capacity that can be sustainably produced, the proposed method is used with a slight modification that takes land availability into consideration. The data shows that the sustainable extractable geothermal resources are significantly less than the technical potential. While utilizing the sustainable power capacity may limit the contribution of geothermal energy in certain regions of the world, there is still enough capacity to meet the growing energy demand in the future, especially in an energy system with high proportions of renewable energy resources.

Van Wees et al. (2013) provided an overview of the outlook for each country, including the economic potential for 2030 and 2050. That study assumed an LCoE of less than 150 EUR/MWh for 2030, and less than 100 EUR/MWh for 2050. As financial support for geothermal energy varies among countries, the economic geothermal potential is presented as stacked potential of the depths down to 7 km by 2030 and 10 km by 2050, based on the assessed cutoff values. Table 4.4 shows that cutoff economic values of 150 EUR/MWh for 2030 and 100 EUR/MWh for 2050, will result in minimal economic potential.

Table 4.4. Geothermal economic potential of European countries in electricity production (TWh) for various depths and LCoE values (van Wees et al., 2013)

Country	*Geothermal economic potential (TWh)*		*Country*	*Geothermal economic potential (TWh)*	
	7 km depth (2030) (≤150 €/MWh)	*10 km depth (2050) (≤100 €/MWh)*		*7 km depth (2030) (≤150 €/MWh)*	*10 km depth (2050) (≤100 €/MWh)*
Austria	0.10	67.10	Latvia	0.01	2.84
Belgium	0	22.28	Lithuania	0.04	17.81

Country	*Geothermal economic potential (TWh)*		*Country*	*Geothermal economic potential (TWh)*	
	7 km depth (2030) (≤150 €/MWh)	*10 km depth (2050) (≤100 €/MWh)*		*7 km depth (2030) (≤150 €/MWh)*	*10 km depth (2050) (≤100 €/MWh)*
Bulgaria	0.10	71.66	Luxembourg	0	2.66
Croatia	3	49.97	Netherlands	0.23	51.76
Cyprus	0	0	Norway	0	0.12
Czech Republic	0.04	30.68	Poland	0	143.56
Denmark	0.03	29.43	Portugal	0.16	62.99
Estonia	0.04	1.67	Romania	0.17	104.65
Finland	0	0	Slovakia	0.89	54.57
France	0.39	653.02	Slovenia	0.01	8.15
Germany	1.37	345.59	Spain	0.52	348.58
Greece	0.47	81.30	Sweden	0	1.03
Hungary	17.06	173.69	Switzerland	0	42.95
Iceland	73.70	321.89	Turkey	62.31	965.91
Ireland	0.19	27.26	UK	0.02	41.81
Italy	12.07	225.83			

When projecting the economic potential of geothermal energy for 2030, it is considered that drilling technology can exploit geothermal energy up to a maximum depth of 7 km cost-effectively. However, it is assumed that by 2050, drilling techniques will advance to enable access to depths of up to 10 km cost-effectively. The objective of ORCHYD is to drill to depths greater than 4 km, thus unlocking the geothermal economic potential of both 2030 and 2050.

The data provided in Table 4.4 are utilized in Section 4.4. for scenario building to assess the impact of drilling technologies on the energy security of certain countries.

During the preparation and installation of an EGS plant, it is vital to thoroughly investigate and study all potential risks, and some restrictions may change over time, requiring re-evaluation during field studies. Population density, water stress, drilling and operational costs are examples of factors that may change over time.

The aforementioned discussion highlights the importance of developing emerging sustainable drilling methods, such as the one that ORCHYD seeks to establish. These methods will help close the gap between the technical and sustainable potential of geothermal energy in Europe.

4.5. Evaluating future scenarios

BP's Energy Outlook 2023 (BP, 2023) considers various pathways to 2050 for the global energy system using three scenarios: accelerated, net zero, and new momentum. The scenarios analyze carbon emissions from energy production, non-energy-related industrial processes, natural gas flaring, and methane emissions. The accelerated and net zero scenarios explore different changes aimed at substantially reducing carbon emissions, while the new momentum scenario reflects the current trajectory of the global energy system. These scenarios have been updated to account for recent events (such as the Russia-Ukraine war), but rather than making specific predictions, they inform BP's beliefs about the energy transition and help shape a resilient strategy for the future.

In BP's Energy Outlook, the future composition of energy demand is defined by four trends: (1) a decrease in hydrocarbons; (2) a rise in renewable energy; (3) a growing electrification of the world, and (4) the adoption of low-carbon hydrogen in processes hard to electrify. Hydrocarbons are expected to decrease as the world shifts towards low-carbon energy sources, and the share of fossil fuels in primary energy is set to decline from 80% in 2019 to below 55% by 2050. Across all three scenarios, there is an expected decline in fossil fuel consumption, which would represent the first sustained fall in demand for any fossil fuel in modern history. Renewable energy is set to expand rapidly and offset the declining role of fossil fuels.

In BP's Energy Outlook, the growth of renewable energy compensates for the reduced use of fossil fuels. The proportion of renewables in global primary energy is expected to rise from approximately 10% in 2019 to between 35% and 65% by 2050, mainly due to the growing prevalence of policies aimed at transitioning to low-carbon energy and the increased cost effectiveness of renewable energy. The share of electricity in total final energy consumption is expected to increase from around a fifth in 2019 to between a third and a half by 2050, underpinned by the continuing electrification of the energy system. In addition, low-carbon hydrogen usage is expected to support the decarbonization of the energy system, particularly in the accelerated and net zero scenarios, with the share of primary energy used in its production increasing to between 13 to 21% by 2050. Finally, global energy demand peaks in all three scenarios due to increased energy efficiency, despite rising living standards in emerging economies, with final energy consumption set to be between 15 and 30% below the 2019 levels by 2050 in the accelerated and net zero scenarios.

However, for the evaluation of future scenarios of geothermal energy intrusion in energy mixes, this report focuses on Europe. A comparison of eight scenarios that aim to achieve over 50% reduction in greenhouse gas emissions by 2030 compared to 1990, and 16 scenarios that aim for climate neutrality by 2050 (similar to the goals of the European Green Deal) is presented in Tsiropoulos et al. (2020). Some scenarios heavily rely on technology, such as the rapid expansion of renewable energy or the implementation of large-scale carbon capture methods. Several scenarios feature a reduction in energy demand through increased efficiency, whether that be through more efficient conversion of energy, more efficient systems such as circular economies, or more efficient use of energy in end-use applications such as building renovations. Other scenarios focus on deploying new energy sources or vectors, such as green hydrogen, or maximizing the electrification of end-use applications. Lastly, some scenarios feature disruptive innovations that change demand patterns, whether that be through technological innovations like digitalization and automation or through behavioral changes such as altered diets, carpooling, or lifestyle shifts.

Tsiropoulos et al. (2020) highlight similarities and differences among the scenarios regarding changes in the EU energy system by 2030 and 2050. Energy projections for 2030 indicate that the proportion of renewable electricity in the EU28 will range from 48% to 70%, which is a significant increase from the current share of 38.4% in 2022 (Jones et al., 2023). Although the total energy consumption in the EU28 decreased at an average annual rate of 0.16% between 1990 and 2014, the consumption of renewable energy increased at a much higher rate of 4.37% annually. It is projected that if this growth rate continues, the EU could raise the percentage of renewable energy in its power system to 50% by 2030 (Wang & Zhan, 2019). In 2050, Europe's electricity supply is likely to be predominantly powered by renewable sources, ranging from 75% to 100% (Tsiropoulos et al., 2020).

The REPowerEU Plan was formulated as a response to the challenges and global energy market disruptions caused by Russia's invasion into Ukraine. Its primary objective is to reduce energy consumption, increase clean energy production, and diversify the European Union's energy supply. EC (2022) has projected that the renewable energy share in the electricity (RES-E) sector will reach 69% under the REPowerEU Plan by 2030. However, this ambitious goal will require significant increases in renewable capacity shares for solar PV and wind. The integration of geothermal energy into the EU's energy mix could help achieve this target faster. Innovative geothermal drilling techniques, such as the one developed in ORCHYD, can make the exploitation of geothermal energy more economically viable, increasing its contribution to the electricity mix and aiding the REPowerEU Plan in achieving its objectives.

The EU's energy and climate policy aims to significantly reduce carbon dioxide emissions in the power sector by 2030, and achieve a carbon-free electricity sector between 95% and 100% by 2050 (EC, 2018). The promotion of wind and solar electricity generation is considered crucial to achieving these policy objectives. However, renewable electricity generation from wind and solar power differs from traditional thermal power generation in that it is dependent on weather conditions and cannot be regulated to match electricity demand. This intermittency can be countered by the development of geothermal energy, which is stable and unaffected by weather as an energy source. EGS is characterized as a breakthrough technology (ECF, 2010) that could potentially cover a share of electricity demand in Europe by 2050. However, a significant ramp-up of EGS can be expected after 2030, when technological and economic constraints, mainly related to drilling technologies, are expected to be addressed.

The following analysis attempts to project how the electricity mix of Europe would be transformed if ORCHYD and relevant geothermal drilling technologies are successful in making more of the geothermal potential of European countries technologically and economically exploitable. Additionally, it considers how such developments may impact energy security.

4.5.1. Scenario building

Geothermal energy has high potential and cost competitiveness, but its contribution to global electricity generation has been limited due to current technology. The economic potential of geothermal energy depends on the optimal depth and minimum cost of production. A study (Aghahosseini & Breyer, 2020) shows that shallow depths are suitable for district heating networks, while deeper depths are more favorable for electricity production. The minimum LCoE is achieved through optimal drilling depth. Electricity production increases with deeper depths, reducing the LCoE despite higher drilling and surface plant costs. Shallower depths, on the other hand, result in lower electricity production despite cheaper drilling costs due to limited heat content.

Studies that focus on geothermal potential estimation (van Wees et al., 2013; Aghahosseini & Breyer, 2020; Chamorro et al., 2013) predominantly examine the electricity generation potential and provide relevant data for each country, in contrast to the heating potential where sufficient data for the current analysis are not provided. Specifically, data retrieved from van Wees et al. (2013) are considered more suitable for this analysis as the study correlates the economic potential of geothermal energy with the drilling depths of selected reference years. In particular, the geothermal potential for electricity production down to 7 km is considered economically exploitable by 2030 and down to 10 km by 2050. The study uses several assumptions which are considered for the current analysis, as well, and are described in a following paragraph. Thus, It should be highlighted that based on the aforementioned, the current analysis will consider exclusively the effect of geothermal energy on the electricity generation projections for various countries, based on assumptions for optimal drilling depths at respective LCoE values for 2030 and 2050.

The effect of enhancement of geothermal drilling technologies, as the one ORCHYD seeks to establish, is examined through this analysis. Contemporary drilling techniques are presently unable to extract most of the Earth’s internal heat, which is stored in depths greater than 5 km (Jolie et al., 2021). As resource assessment studies show (van Wees et al., 2013; Aghahosseini & Breyer, 2020; Chamorro et al., 2013), in order to reach untapped geothermal potential especially in depths between 7 and 10 km, new drilling concepts are needed, which will ensure economic viability and sustainability of geothermal production. Traditional drilling systems have been designed to perform optimally in oil and gas reservoirs.

The unique characteristics of geothermal reservoirs require a fresh perspective on available systems (Kiran et al., 2022) and face significant cost-related challenges (Vonsée, van Ruijven, & Liu, 2019). While the estimated cost of electricity generated from EGS projects is currently 0.09€ /kWh (Chandrasekharam et al., 2022), advancements in drilling technology, such as the ones ORCHYD seeks to establish, are expected to lower this cost. As cost reductions make geothermal energy more competitive with other renewable energy technologies, it is expected to secure a significant share of electricity production in Europe by 2050 (Longa et al., 2020).

In order to assess the potential of geothermal energy in the energy mix of European countries from 2020 to 2050, several parameters must be considered, and certain assumptions must be made. Projections of European electricity consumption are needed to estimate the demand. The RES percentage in the energy mix must also be projected for 2030 and 2050. Finally, to understand better the potential of geothermal energy to transform Europe's energy security, projections of economically recoverable geothermal electricity must be compared to electricity consumption and the penetration of renewable energy sources (RES) in the energy mix.

Bogdanov et al. (2019) and van Wees et al. (2013) provided projections for the annual electricity consumption in TWh for 2030 and 2050. Eurostat (2023a) provided data on the share of renewables in the energy mix of each country for 2020. Projections for the share of renewable energy sources (RES) in the electricity production mix were based on scenarios developed by Tsiropoulos et al. (2020) and Wang & Zhan (2019).

Van Wees et al. (2013) provided projections for the economic potential of geothermal energy for each European country in 2030 and 2050, as shown in Table 4.4 previously. The study's assumptions regarding LCoE values of less than 150 EUR/MWh for the 2030 scenario and less than 100 EUR/MWh for the 2050 scenario were taken into account in constructing the scenarios. A maximum reachable depth of 7 km was considered for geothermal potential values in 2030, while a maximum depth of 10 km was deemed achievable for 2050 estimations, owing to advancements in drilling technology. The significance of the ORCHYD project's contribution to unlocking geothermal potential in both the 2030 and 2050 ranges is evident.

At times, the available geothermal economic potential for 2050 was found to exceed the share of RES in the electricity production mix, in which case, it was assumed that geothermally produced electricity would cover the total RES share of electricity production. Any remaining economic geothermal potential was assumed to remain underutilized.

The scenarios were developed to account for the upper limit of the possible geothermal contribution to the electricity generation mix for Europe, taking into consideration the estimated technological enhancements. The percentage of geothermal share in the electricity mix of the examined countries and regions may be lower than the considered value, depending on the possible technological breakthroughs of other renewable energy sources, state policies, or investment opportunities.

The years 2030 and 2050 were chosen as convenient milestones given their coverage in the published literature and the existence of official EU targets for those years (e.g. https://www.europarl.europa.eu/factsheets/en/sheet/70/renewable-energy). Three distinct scenarios were created for both 2030 and 2050, each with a target RES share in the electricity production mix and a corresponding annual growth rate (Table 4.5).

Table 4.5. EU RES scenarios for 2030 and 2050

Scenario	*Start year*	*End year*	*RES share in electricity mix at end of time period (%)*	*Annual growth rate of RES share in electricity mix (%)*	*Comments*
2030_A	2020	2030	42	1.8	Pessimistic view, considering the possibility of a slowdown of energy transition
2030_B	2020	2030	50	4	Intermediate view of the evolution of energy transition
2030_C	2020	2030	60	6.5	Optimistic view of the evolution of energy transition, taking into account the implications of the Russian invasion of Ukraine by counterbalancing the optimistic

Scenario	*Start year*	*End year*	*RES share in electricity mix at end of time period (%)*	*Annual growth rate of RES share in electricity mix (%)*	*Comments*
					scenarios of Tsiropoulos et al. (2020) with the analysis of Wang and Zhan (2019)
2050_A	2020	2050	65	2.7	Pessimistic view, considering the possibility of a slowdown of energy transition
2050_B	2020	2050	80	4	Intermediate view of the evolution of energy transition
2050_C	2020	2050	100	5.1	Optimistic, under the prism of the 2050 long term strategy of the EU (https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en). Contrary to the other scenarios, the use of natural gas and nuclear energy are considered to be terminated (Tsiropoulos et al., 2020).

The success of the energy transition relies not solely on the availability of RES but also on how different RES can work together in various regions. Despite its relatively small geographical size, Europe comprises vastly different regions, including the windy British Isles, Norway with its abundant hydropower potential, the sunny Mediterranean, and other countries with a blend of these extremes. Taking into account the interconnectivity of grids (Bogdanov et al., 2019, Suppl. Table 4), the following geographic regions are named as follows, and considered in the rest of the analysis:

- AusHun: Austria and Hungary
- Baltics: Estonia, Latvia and Lithuania
- BENELUX: Belgium, Netherlands, and Luxembourg
- British Isles: UK and Ireland
- CzeSlov: Czech Republic and Slovakia
- Iberia: Spain and Portugal
- SE Europe: Greece, Cyprus, Romania, and Bulgaria
- West Balkans: Slovenia and Croatia.

The scenarios developed examine and make projections on:

a) The penetration of RES in the electricity energy production for the periods 2020-2030 and 2020-2050.

b) The upper limit of the share of geothermal energy in the respective RES share in the electricity energy production for the respective periods. In certain instances, the economic potential for geothermal energy in 2030 and 2050 exceeded the proportion of renewable energy sources (RES) in the electricity production mix. In these cases, it was assumed that geothermal power would fully cover the RES share of electricity production, while the remaining geothermal potential would be left untapped.

c) The share of geothermal energy production in the total electric energy consumption for the respective periods.

The baseline 2020 scenario and the results of the analysis of the other scenarios for 2030 and 2050 are presented in Tables 4.6, 4.7 and 4.8.

2020 baseline scenario

The baseline scenario for 2020 is shown in Table 4.6, with the average RES share in electricity production across Europe being 35.4% (Eurostat, 2023b).

Table 4.6. Baseline scenario of 2020 for the energy mix of European countries and regions

Country or region	*RES in electricity production (%)*	*Electricity generation (TWh)*	*Electricity generation from RES (TWh)*	*Geothermal electricity generation (TWh)*	*Geothermal share in consumption (%)*	*Geothermal in RES generation (%)*
AusHun	28.94	103.97	30.089	0.016	0.02	0.05
Baltics	33.39	16.33	5.452	0	0	0
BENELUX	13.57	211.9	28.759	0	0	0
British Isles	40.57	339.34	137.656	0	0	0
CzeSlo	17.3	108.66	18.798	0	0	0
Denmark	31.7	28.73	9.107	0	0	0
Finland	43.9	68.72	30.168	0	0	0
France	19.1	527.25	100.705	0.133	0.03	0.13
Germany	19.1	567.26	108.347	0.231	0.04	0.21
Iberia	23.32	311.27	72.586	0.218	0.07	0.3
Iceland	83.7	19.13	16.012	5.961	31.16	37.2
Italy	20.4	278.07	56.726	6.026	2.17	10.62
Norway	77.4	153.3	118.654	0	0	0
Poland	16.1	157.14	25.3	0	0	0
SE Europe	24.17	148.85	35.982	0	0	0
Sweden	60.1	163.79	98.438	0	0	0
Switzerland	76	67.4	51.224	0	0	0
Turkey	16.8	305.42	51.311	10.028	3.28	19.54
West Balkans	27.64	30.13	8.327	0.094	0.31%	1.13

Three European countries have a significant contribution to their electricity generation from geothermal energy:

- In Iceland, 31.16% of electricity consumption was produced from geothermal energy, representing 37.23% of the country’s total electricity generation from RES.
- In Turkey, 3.28% of electricity consumption in the country was produced from geothermal energy, representing 19.54% of the country’s total electricity generation from RES.
- Finally, in Italy, 2.17% of electricity consumption in the country was produced from geothermal energy, representing 10.62% of the country’s total electricity generation from RES.

The baseline scenario data were used as a basis for the calculation of the data of the other scenarios, as explained in the following paragraphs.

2020-2030 scenario

In 2022, the share of renewable energy in gross electricity consumption in the EU was 38.4% (Jones et al., 2023). For the 2020-2030 decade, our scenarios expect RES to secure a share in electricity production ranging from 42% for the pessimistic 2030_A scenario, to 50% for the intermediate 2030_B scenario, and up to 60% for the optimistic 2030_C scenario. Detailed data derived from these scenario targets broken down by country or region are presented in Table 4.7, with an explanation of how they were derived following the table.

Table 4.7. Scenarios for the energy mix of European countries and regions by 2030

Country or region	*Electricity consumption (TWh)*	*2030_A RES in electricity production (%)*	*2030_B RES in electricity production (%)*	*2030_C RES in electricity production (%)*	*Geothermal economic potential (TWh)*	*Upper limit of geothermal share in consumption (%)*	*2030_A Geothermal in RES generation (%)*	*2030_B Geothermal in RES generation (%)*	*2030_C Geothermal in RES generation (%)*
AusHun	122.16	34.59	42.84	54.32	17.16	14.05	40.61	32.79	25.86
Baltics	28.52	39.91	49.42	62.67	0.09	0.32	0.79	0.64	0.5
BENELUX	245.28	16.22	20.09	43.77	0.23	0.09	0.58	0.47	0.21
British Isles	461.32	48.49	60.05	76.15	1.02	0.22	0.46	0.37	0.29
CzeSlo	128.08	20.68	25.61	32.47	0.93	0.73	3.51	2.84	2.24
Denmark	43.67	37.89	46.92	59.51	0.03	0	0.18	0.15	0.12
Finland	90.83	52.47	64.98	82.41	0	0	0	0	0
France	640.64	22.83	28.27	35.85	7.53	1.18	5.15	4.16	3.28
Germany	640.64	22.83	28.27	35.85	15.6	2.44	10.67	8.61	6.79
Iberia	402.15	27.87	34.52	43.77	0.91	0.23	0.81	0.66	0.52
Iceland	20	100	100	100	73.7	368.5	100	100	100
Italy	340.09	24.38	30.2	38.29	12.07	3.55	14.55	11.75	9.27
Norway	137	92.52	100	100	0	0	0	0	0
Poland	177.51	19.24	23.83	30.22	0	0	0	0	0
SE Europe	191.41	28.89	35.78	45.38	1.88	0.98	3.4	2.74	2.16
Sweden	167.32	71.84	88.96	100	0	0	0	0	0
Switzerland	73	90.84	100	100	1.13	1.55	1.7	1.55	1.55
Turkey	469	20.08	24.87	31.54	62.31	13.29	66.16	53.42	42.13
West Balkans	101	33.03	40.91	51.88	3.01	2.98	9.02	7.28	5.74

Projections of the electricity consumption (in TWh) for the countries and regions included in Table 4.7 were retrieved from van Wees et al. (2013) and Bogdanov et al. (2019). Projections for the geothermal economic potential (in TWh) were retrieved from van Wees et al. (2013). The electricity consumption projections (in TWh) for the countries and regions listed in Table 4.7 were obtained from two sources, namely van Wees et al. (2013) and Bogdanov et al. (2019). Similarly, the projections for geothermal economic potential (in TWh) were obtained from van Wees et al. (2013).

Using data for 2020 (Table 4.6) and the annual growth rates of each scenario, RES in electricity production (%), RES electricity production (TWh), the upper limit of geothermal share in consumption (%), and the geothermal energy share in RES generation (%) were calculated as follows for all scenarios:

RES in electricity production for year and scenario (%) =
RES in electricity production for 2020 (%) ×
Annual growth rate for year and scenario (%)

RES in electricity production for year and scenario (TWh)$_{y,s}$ =
RES in electricity production for year and scenario (%) ×
Electricity consumption for year (TWh)

Upper limit of geothermal share in consumption for year (%) =
100 × Geothermal economic potential for year (TWh) /
Electricity consumption for year (TWh)

Geothermal in RES generation for year and scenario (%) =
100 × Geothermal economic potential for year (TWh) /
RES electricity production for year and scenario (TWh)

Geothermal energy could acquire a noteworthy share in the European electricity production mix until 2030 as certain countries could diversify their electricity mix through geothermal production. For instance, Iceland stands out as a remarkable example, as its geothermal capacity could fulfill 100% of its electricity consumption needs and represent 368.5% of its total renewable energy generation. Austria and Hungary show significant reliance on geothermal energy, with its contribution reaching as high as 14.05% of their electricity consumption and accounting for a substantial portion of their renewable energy generation. Turkey follows closely with 13.29% of electricity consumption being supplied by geothermal sources. Other countries like Italy, Croatia, Slovenia, Germany, Switzerland, France, Greece, Cyprus, Romania, and Bulgaria also exhibit varying degrees of utilization, ranging from 0.98% to 3.55% of electricity consumption, contributing to their overall renewable energy generation. These figures indicate the potential for hydrothermal geothermal systems to play a substantial role in future energy scenarios, providing clean and sustainable electricity in these regions.

2020-2050 scenario

RES are expected to secure a significant share in electricity production for the period 2020-2050, with the share ranging from 65% in the pessimistic scenario 2050_A, to 80% in the intermediate scenario 2050_B, where nuclear energy is assumed to continue operation, and up to 100% in the optimistic scenario C, where all nuclear energy is assumed to be phased out. Details of these scenarios are presented in Table 4.8.

Table 4.8. Scenarios for the energy mix of European countries and regions by 2050

Country or region	*Electricity consumption (TWh)*	*2030_A RES in electricity production (%)*	*2020_B RES in electricity production (%)*	*2030_C RES in electricity production (%)*	*Geothermal economic potential (TWh)*	*Upper limit of geothermal share in consumption (%)*	*2030_A Geothermal in RES generation (%)*	*2030_B Geothermal in RES generation (%)*	*2030_C Geothermal in RES generation (%)*
AusHun	149.31	64.36	81.63	100	240.79	161.27	100	100	100
Baltics	34.86	74.25	95.49	100	23.22	66.61	89.71	69.76	66.61
BENELUX	299.78	30.18	44.02	100	76.7	25.59	84.77	58.12	25.59
British Isles	563.84	90.21	95.53	100	69.06	12.25	13.58	12.82	12.25
CzeSlo	156.53	38.47	56.11	100	85.25	54.46	100	97.06	54.46
Denmark	53.38	70.5	100	100	29.43	55.13	78.21	55.13	55.13
Finland	111.01	97.63	100	100	0	0	0	0	0
France	783	42.48	61.95	100	653.02	83.4	100	100	83.4
Germany	864.08	42.48	61.95	100	345.59	40	94.16	64.56	40
Iberia	491.51	51.86	73.93	100	411.58	83.74	100	100	83.74
Iceland	26	100	100	100	321.89	1238.04	100	100	100
Italy	415.67	45.37	66.17	100	225.83	54.33	100	82.11	54.33
Norway	174	100	100	100	0.12	0.07	0.07	0.07	0.07
Poland	216.96	35.8	52.22	100	143.56	66.17	100	100	66.17
SE Europe	233.95	53.76	78.4	100	257.61	110.11	100	100	100
Sweden	204.5	100	100	100	1	0.49	0.49	0.49	0.49
Switzerland	93	100	100	100	42.9	46.13	46.13	46.13	46.13
Turkey	649	37.36	54.49	100	965.9	148.83	100	100	100
West Balkans	123	61.46	89.4	100	58.12	47.25	76.88	52.86	47.25

As geothermal energy is projected to acquire a significant share in the European electricity production mix by 2050, geothermal energy would appear in the electricity consumption profile of more countries. Iceland, in particular, demonstrates the remarkable utilization of geothermal power, with its capacity being able to fulfill 100% of its electricity consumption needs and representing an astounding 1238.04% of its total renewable energy generation. Austria and Hungary show a substantial reliance on geothermal energy, with a range between 64.43% and 100% of electricity consumption being supplied by geothermal sources, representing 100% of their total renewable energy generation. Turkey follows closely, with a range between 37.36% and 100% of electricity consumption coming from geothermal sources, representing 100% of the total renewable energy generation. Greece, Cyprus, Romania, and Bulgaria also exhibit significant potential, with a range between 53.76% and 100% of electricity consumption being sourced from geothermal energy, accounting for 100% of their total renewable energy generation. The future scenarios also highlight the contributions of geothermal energy in France, Spain, Portugal, Denmark, Poland, the Czech Republic, Slovakia, Estonia, Latvia, Lithuania, Germany, Italy, Croatia, Slovenia, Switzerland, Belgium, Netherlands, Luxembourg, Ireland, the UK, and Norway, with varying percentages of electricity consumption being fulfilled by geothermal sources. These findings emphasize the substantial role geothermal energy can play in achieving sustainable and renewable electricity generation in these countries.

4.5.2. Energy security index in scenarios

This last section of the report analyzes how the scenarios affect the energy security of certain European countries.

To calculate projections for the energy security index, it is necessary to first develop projections for the individual indicators that represent the dimensions and are used to compute the index. In light of the absence of historical data that would allow projections for the complete set of indicators outlined in Section 4.2, a more concise energy security index was developed, comprising the following dimensions and indicators:

1. The dimension of *physical availability* was proxied by electricity generation (TWh), oil reserves (billion barrels), electricity exports (TWh), RES (excluding geothermal) share in electricity consumption (%), geothermal share in electricity consumption (%), and EGS sustainable potential (GWe).
2. The dimension of *technology development* was proxied by electricity generation capacity (GW).
3. The dimension of *economic affordability* was proxied by GDP per capita ($).
4. The dimension of *social accessibility* was proxied by electricity imports (TWh).
5. The dimension of *governance* was proxied by military spending (% of GDP).
6. The dimension of *manmade threats* was proxied by the length of coastline (% of total borders).
7. Finally, the dimension of the *natural environment* was proxied by carbon dioxide emissions per capita (tonnes per capita), and share of agricultural land (%).

Of these indicators, electricity generation (TWh), RES (excluding geothermal) share in electricity consumption (%), geothermal share in electricity consumption (%), and coastline (% of total borders) were taken from the literature. The rest, oil reserves (billion barrels), electricity exports (TWh), electricity generation capacity (GW), GDP per capita ($), electricity imports (TWh), military spending (% of GDP), carbon dioxide emissions per capita (tonnes per capita), and share of agriculture land (%), were forecast.

Data availability was further limited by the periodicity of the EGS sustainable potential indicator, sourced from the literature and updated every five years (Aghahosseini & Breyer, 2020). To identify the most appropriate forecasting model, we compared the performance of various techniques using 5-year historical data from 1980 to 2020. The techniques considered included random walk with drift, Brown's linear and quadratic exponential smoothing, Holt's linear exponential smoothing, and autoregressive integrated moving average (ARIMA) models. For ARIMA models, nonstationary time series data were transformed into stationary data by calculating first or second differences based on the smallest standard deviation criterion.

Due to the limited time series data availability (8 data points from 1980 to 2020 at 5-year intervals), we chose to develop forecasts for 2025 and 2030. As a result, we only consider the 2030_A, 2030_B, and 2030_C scenarios. The rankings for the energy security index projections differ from those of the 2020 baseline scenario. This is because we utilized the concise energy security index and a different set of countries (chosen based on the availability of time series data) for the projections. Consequently, we recalculated the z-scores for all indicators and the energy security index for the new set of countries.

The final results are presented in Table 4.9.

Table 4.9. Changes in the index rankings of the examined countries between 2020 and 2030

2020 Energy security index ranking	Country	2020 Energy security index	2030_A and 2030_B Energy security index Ranking (changes)	Country	2030_A Energy security index	2030_B Energy security index	2030_C Energy security index Ranking (changes)	Country	2030_C Energy security index
1	Norway	0.688	2⇒1	France	0.763	0.760	2⇒1	France	0.759
2	France	0.548	1⇒2	Norway	0.668	0.664	3⇒2	UK	0.674
3	UK	0.431	3	UK	0.651	0.658	1⇒3	Norway	0.646
4	Turkey	0.214	4	Turkey	0.398	0.394	4	Turkey	0.392
5	Denmark	0.172	8⇒5	Spain	0.146	0.143	8⇒5	Spain	0.144
6	Iceland	0.143	7⇒6	Sweden	0.078	0.094	7⇒6	Sweden	0.097
7	Sweden	0.116	5⇒7	Denmark	0.027	0.029	5⇒7	Denmark	0.037
8	Spain	0.011	9⇒8	Greece	-0.040	-0.043	9⇒8	Greece	-0.041
9	Greece	-0.041	13⇒9	Switzerland	-0.083	-0.084	13⇒9	Switzerland	-0.102
10	Ireland	-0.092	10	Ireland	-0.109	-0.114	10	Ireland	-0.117
11	Portugal	-0.140	12⇒11	Italy	-0.195	-0.198	12⇒11	Italy	-0.198
12	Italy	-0.177	11⇒12	Portugal	-0.253	-0.249	11⇒12	Portugal	-0.239
13	Switzerland	-0.279	14⇒13	Netherlands	-0.276	-0.282	14⇒13	Netherlands	-0.286
14	Netherlands	-0.345	6⇒14	Iceland	-0.429	-0.425	6⇒14	Iceland	-0.427
15	Belgium	-0.618	15	Belgium	-0.592	-0.598	15	Belgium	-0.603
16	Austria	-0.632	16	Austria	-0.753	-0.748	16	Austria	-0.737

In terms of geothermal energy advancements and their impact on the 2030 energy security index, it is important to highlight the progress made in drilling technology towards achieving the ORCHYD goal depths. Looking ahead to changes in the energy security index rankings between 2020 and 2030, several noteworthy shifts can be observed. France is projected to rise from the 2nd to the 1st position, showcasing their commitment to securing a reliable energy future. Spain is anticipated to climb from the 8th to the 5th place, demonstrating their efforts to strengthen energy security. Similarly, Sweden is expected to improve their standing from the 7th to the 6th place, signifying their dedication to enhancing energy stability. Greece is projected to move from the 9th to the 8th position, indicating their progress towards a more secure energy landscape. Switzerland is set to make significant strides, moving from the 13th to the 9th position in the rankings, exemplifying their commitment to energy security. Italy, though only moving from the 12th to the 11th position, shows their determination to continuously improve. Additionally, for the 2020-2030 index rankings among the examined countries for scenario C, the UK is projected to move from the 3rd to 2nd position of the energy security index rankings. Lastly, the Netherlands is projected to advance from the 14th to the 13th position, underscoring their ongoing efforts to strengthen their energy security profile. These changes in the index rankings reflect the collective pursuit of a more stable and secure energy future across these nations.

Although the changes in the energy index values may appear minor, it is important to consider that the absolute scores of the energy security index are influenced by the values of the energy security index of the other countries in the sample. Therefore, it is the changes in the energy security rankings that provide significant insights.

While it is currently not possible to make projections for 2050 due to limited data availability, it is reasonable to anticipate significant improvements in energy security through the use of drilling technologies that can reach target depths of 7-10 km. These advancements would enable the exploitation of extensive geothermal reservoirs and lead to increased electricity generation from geothermal sources.

It is worth noting that Iceland is projected to achieve a surplus in both 2030 and 2050, while countries such as Greece, Cyprus, Austria, Hungary, Romania, Bulgaria, and Turkey are expected to achieve a surplus in 2050, with their electricity production meeting their electricity demand projections. Such surpluses can be directed through interconnected grids to neighboring countries and regions with electricity demand deficits. This will enhance the energy security of the European continent and provide economic profit for the respective producing countries.

However, in cases like Iceland, the incremental improvements in geothermal drilling technology that increase electricity generation capacity may not be practically advantageous. This is because Iceland has a relatively low electricity demand compared to its vast generating capacity, which is further compounded by the lack of interconnectivity with the power grids of other countries. The progress of energy storage technologies could give countries like Iceland a competitive edge, enabling them to become net energy exporters.

5. Conclusions and recommendations

This final section of the report provides a summary, draws conclusions, highlights any limitations, and offers a few recommendations. This work extends the scope of previous tasks by examining ORCHYD's impact on energy security.

Following an extensive literature review, a custom-made quantitative index of energy security was formulated, selecting seven appropriate dimensions and 33 indicators as metrics of the dimensions. The energy security index was calculated by aggregating the corresponding subindexes that represent the seven dimensions of energy security: physical availability, technology development (which also represents the role of geothermal energy), economic affordability, social accessibility, governance, manmade threats, and natural environment. The indicator values, obtained from a baseline year of 2020, were standardized and averaged with weights assigned to each dimension by an ad-hoc energy expert panel. Energy security values were then calculated.

The countries were then ranked in descending order based on their energy security index values. Scandinavian countries and the US received high rankings in the energy security index, thanks to their high scores across most dimensions. On the other hand, Turkey, India, and Bulgaria received low rankings due to their poor performance across the dimensions.

Turning to the future, changes in the level of energy security were evaluated for pessimistic, intermediate, and optimistic future scenarios targeting the years 2030 and 2050. A smaller number of indicators with available historical data were forecast using appropriate time series methods, and a more concise version of the energy security index was calculated for selected countries and regions with available data. The energy security index of some countries was found to either improve or worsen, causing their position in the ranking to change by one place.

In conclusion, advancements in geothermal drilling techniques, such as those pursued by ORCHYD, could make the geothermal potential of European countries exploitable to a greater extent and thus, contribute to:

- An estimated 3.65% of the total electricity consumption in the European countries examined by 2030.
- An estimated 70% of the total electricity consumption in the European countries examined by 2050.
- A surplus of electricity production in Iceland, Greece, Cyprus, Romania, Hungary, Austria, Bulgaria, and Turkey.

The enhancement of energy security in European countries and the promotion of energy transition will be facilitated by this measure, while also contributing to the geopolitical goal of reducing the EU's reliance on imported fossil fuels such as Russian natural gas.

ORCHYD's primary objective is to develop advanced geothermal drilling technologies capable of accessing depths greater than 4 km. By utilizing these advancements, countries can explore deeper reservoirs and expand their sustainable geothermal potential. Deeper drilling can access higher-temperature resources, enabling power generation and ultimately increasing energy production. As a result, countries can leverage geothermal energy to reduce dependence on nonrenewable sources, achieve a more sustainable and reliable energy supply, and promote economic growth and development.

The research reported herein employed a quantitative approach to assess energy security, which was constrained by data availability for the 35 countries studied. However, the geothermal energy security index has the flexibility to be used for any country or region of the world with sufficient data. Moreover, the index can be customized by adding and refining indicators in each sub-category to enhance the comparison and evaluation of energy security across countries. This adaptability makes the geothermal energy security index a valuable tool for policymakers and researchers seeking to assess energy security and promote sustainable energy practices worldwide.

A comprehensive and unbiased evaluation of energy security across countries or regions requires access to sufficient data. The geothermal energy security index can forecast future scenarios if projections for all indicators are available. However, even if data is incomplete, the index can still be calculated and used to generate a comparative ranking of the studied countries, provided that at least one indicator per category is available. To gain a deeper understanding of advanced technologies such as those developed by ORCHYD, it is necessary to have data on the electricity production potential of geothermal reservoirs at various depth ranges.

While scenario-building projections for 2030 and 2050 are useful tools for anticipating future energy trends, they are subject to certain limitations. For instance, these projections may be constrained by geographical considerations and may not account for "black swan" events, such as wars or technological disruptions that could significantly alter the energy landscape. One risk scenario that has not been fully explored is the possibility of a colder-than-normal winter in Europe, which could lead to a depletion of gas storage, energy rationing, and negative impacts on energy-intensive industries. This could potentially prompt European governments to turn to coal-fired power generation, hindering the region's efforts to combat climate change (The Economist Intelligence Unit, 2022).

According to Gong et al. (2023), there are currently 30 EGS projects operating worldwide, with 14 of them capable of generating power and 5 in routine operation, amounting to a total installed capacity of 12.2 MW. However, to fully realize the potential of EGS and increase its global energy contribution, innovative approaches such as those developed by ORCHYD are essential. Future research should also focus on finding ways to optimize geothermal energy production, enhance operational efficiency, and integrate geothermal energy into existing energy systems via district heating and cooling, as well as hybridization with other renewable energy sources.

Future research on energy security could prioritize the development of new energy storage technologies to mitigate the intermittency of renewable energy sources (Azzuni & Breyer, 2018), as well as exploring decentralized energy systems to enhance resilience and reduce vulnerability to disruptions (Weinand, Scheller, & McKenna 2020). Additionally, cybersecurity solutions should be developed and implemented to safeguard against cyberattacks on energy infrastructure (Tvaronavičienė et al., 2020), which could threaten the stability of entire energy systems. Developing data management systems, numerical simulators, and assessment methods are also critical. To further enhance energy security and sustainability, it is also crucial to analyze the impact of changing global energy dynamics and to prioritize energy efficiency across all sectors. These efforts can lead to greater energy security and sustainability.

Geothermal mapping, resource assessment techniques, and exploration can benefit from the development of new tools and models, as well as geophysical, geochemical, and drilling technologies to reduce risks and costs. Carbon dioxide can be used as a working fluid in EGS to increase heat extraction rates and lower carbon emissions (Pruess, 2006). Studies could also explore ways to optimize geothermal energy production, improve operational efficiency, and integrate geothermal energy into existing energy systems. Utilizing policy tools such as tax incentives, feed-in tariffs, direct subsidies, and grants can aid in the development of geothermal projects (Coro & Trumpy, 2020; Ciriaco, Zarrouk, & Zakeri, 2020).

The qualitative research interviews planned for Task 3.4 (Expert interviews and geopolitical perspective) will provide valuable insights to energy security. Those data will complement the findings of Task 3.3 and add more detail and nuance to the knowledge gained in this report.

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Appendix: History of energy security

According to Yergin (1991), Winston Churchill believed that oil supply security was essential to fuel his army during World War I. It was a paramount concern for Germany and Japan as they invaded the Soviet Union (USSR) and Indonesia during World War II. During these wars, energy security was often implicitly used as a synonym for national security, as the notion of energy security was closely tied to the supply of fuels for the military (Cherp & Jewell, 2011). In 1960, oil-exporting countries formed the Organization of Petroleum Exporting Countries (OPEC) to address the distribution of wealth derived from oil exports. In that period, the security of energy supply was not a priority in many developing countries, because companies supplied cheap oil and, thus, stability. Until the 1970s, the concept of energy security that explicitly linked supply security to state survival was not used in national security discourse.

Concerns about energy security arose in the early 1970s in Europe, Japan, and the United States (US), as the first oil crisis in 1973 revealed the vulnerability of developed economies to oil price shocks. The Organization of Arab Petroleum Exporting Countries (OAPEC) introduced an oil embargo on many countries, the reason for the embargo being the Yom Kippur War, which was not energy-related. This became known as the oil weapon, i.e. using oil as leverage for political gains (Gasser, 2020). Political analysts have conceptualized security as a grand strategy that encompasses both war and peaceful diplomacy (Cherp & Jewell, 2011).

As a result, the International Energy Agency (IEA) was established in 1974 by the Organization for Economic Cooperation and Development (OECD) to promote energy security through collective response to physical supply disruptions. Every member state of the IEA is required to keep stocks equal to at least 90 days of net oil imports. Following the 1973 oil shock, many developed countries made energy security a matter of national security. A similar situation happened in 1979 during the second oil crisis. Due to the Iranian Revolution, the global oil supply decreased, and prices doubled over one year. Consequently, by the end of 1970, energy security was a high-priority issue on the policy agenda, given its importance to the economy. At the same time, energy security came to be associated with reducing reliance on oil consumption.

The 1980s saw a reduction in energy security concerns due to increased supply and decreased demand for energy. Natural gas and nuclear energy partially replaced oil, particularly for power generation. Energy security studies have changed in scope and focus over time, evolving from classic political economy studies of oil supplies for industrialized democracies to a research field addressing a much wider range of energy sectors and energy security challenges (Cherp & Jewell, 2014). The sources that Cherp and Jewell cite show that, in the 1970s and 1980s, energy security signified the stable supply of cheap oil. Threats to energy security included threats of embargoes and price manipulation by exporters.

The first Gulf War and the fall of the Soviet Union defined the 1990s. Following that, energy security gained traction as global resources became scarce in the face of rising global energy demand. The first Gulf War (1990-1991) and the dissolution of the Soviet Union (1991) gave rise to new concepts, while the issue of energy security gained prominence in global discourse (Yergin, 1991). Throughout the decade, global warming issues became more institutionalized. The Kyoto Protocol, signed in 1997, was the first international treaty to outline emission targets. The implementation of the agreement called for participating members to devise policies and measures aimed at reducing and offsetting their domestic emissions, while enhancing the absorption of greenhouse gasses.

According to Yergin (2006) and Hancock and Vivoda (2014), the energy security issue reemerged in the 2000s, driven by rising Asian demand, disruptions in European gas supplies, and pressure to decarbonize energy systems. In 2005, the Russian Federation reduced gas supplies to Ukraine due to their refusal to accept the new prices. As a result, the gas supply to Western Europe was also reduced. The Russian-Ukrainian crises of 2006 and 2009 demonstrated that the EU's leading supplier was unreliable and could use energy resources as a geopolitical weapon. The surge in oil prices until 2008, coupled with geopolitical supply tensions, has renewed global interest in energy security. Terrorist attacks led to simultaneous wars in Afghanistan and Iraq. The Arab Spring and the rise of the Islamic State created tensions and instability. Finally, the Fukushima nuclear disaster in 2011 raised serious concerns about the safety of nuclear power.

The idea of energy security has transformed over time, with the notion of fair pricing being incorporated in the 1970s and 1980s, thus diverging from the original concept of stable energy supply implied by the term. According to Goldthau (2011), energy security has become closely connected with other energy policy issues, such as providing equitable access to modern energy and mitigating climate change. The increasing global focus on energy security is mostly explained by the emergence of new giants of the world economy and their rising energy demand. Table 2.1 summarizes the most significant historical moments in the history of energy security.

Table A1. Historical milestones of energy security

Date	Historical event
July 28, 1914 to November 11, 1918	First World War
July 11, 1924	Foundation of the World Energy Council (WEC)
September 1, 1939 to September 2, 1945	Second World War: From an energy perspective, this era was marked by the failed Nazi invasion of Soviet Russia (Operation Barbarossa, badly timed in respect to the Russian winter), epitomizing the importance of timing a campaign and providing logistical support for an army.
February 4-11, 1945	The Yalta Conference marked the beginning of the Cold War, an era during which oil was provided at preferential prices to country members of the Eastern Block by the Soviet Union (Russia) (https://www.historyonthenet.com/the-cold-war-timeline-2)
1947	Stanolind Oil and Gas (an exploration subsidiary of Amoco) conducted the first experimental fracturing in southwestern Kansas, using gelled gasoline and sand from the Arkansas River (Montgomery & Smith, 2010). Multistage hydraulic fracturing combined with horizontal drilling (60 years later) fueled the shale gas and oil revolution observed presently.
February 1958	Foundation of the European Nuclear Energy Agency (ENEA), which in

Date	Historical event
	1972 was renamed Nuclear Energy Agency (NEA) (https://www.oecd-nea.org/general/history)
September 1960	Foundation of the Organization of Petroleum Exporting Countries (OPEC)
October 6 to 26, 1973	Yom Kippur Arab-Israeli war: an unprecedented era of a war in the Middle East, prelude to the 1st Oil Crisis
October 1973 to March 1974	1st Oil Crisis (Shock): The 1973 (1st) Oil Crisis started when the Organization of Arab Exporting States proclaimed an embargo at nations perceived as supporting Israel during the Yom Kippur war. Cars in the US famously formed lines to purchase a limited quantity of gasoline at gas stations.
November 18, 1974	Establishment of the International Energy Agency (IEA) (https://en.wikipedia.org/wiki/International_Energy_Agency)
April 10, 1975	US Congress instituted an US oil export ban by passing the Energy Policy and Conservation Act (EPCA), as a response to the 1st Oil Crisis.
January 1978 to February 1979	Iranian Revolution: The 1979 Islamic Revolution in Iran began in early 1978 and ended a year later (https://www.britannica.com/event/Iranian-Revolution), when the royal reign of Shah Mohammad Reza Pahlavi collapsed, Sheikh Khomeini took control as grand ayatollah of the Islamic republic (https://www.federalreservehistory.org/essays/oil_shock_of_1978_79), and Iran, a major oil producer and exporter, turns into a theocratic state. As a result of reduced Iranian oil output, the world production of oil declined by 7% (https://econweb.ucsd.edu/~jhamilton/oil_history.pdf), being partially responsible for precipitating the Second Oil Crisis. An extended timeline of events of the Iranian Revolution is presented by the Brookings Institution (https://www.brookings.edu/blog/order-from-chaos/2019/01/24/the-iranian-revolution-a-timeline-of-events/). A detailed timeline of the Iranian Revolution is available at https://www.reuters.com/article/us-iran-revolution-anniversary-timeline/timeline-of-the-iranian-revolution-idUSKCN1Q017W.
1978 to 1979	2nd Oil Crisis (Shock), detailed at https://www.federalreservehistory.org/essays/oil_shock_of_1978_79, a repeat of the global nightmare experienced during the 1st Oil Crisis.
January 23rd, 1980	Carter Doctrine set out by President Jimmy Carter: “An attempt by any outside force to gain control of the Persian Gulf region will be regarded as an assault on the vital interests of the United States of America, and such an assault will be repelled by any means necessary, including military force” (http://www.presidency.ucsb.edu/ws/?pid=33079). The US made clear that it will not allow control of the oil-producing Persian Gulf region by actors inimical to the unhindered operation of the global oil market.

Date	Historical event
August 2, 1990 to February 28, 1991	1st Gulf War: Saddam Hussein's unsuccessful bid to conquer Kuwait and dominate the Persian Gulf, a region of immense geopolitical importance due to its abundance of energy resources. Saddam Hussein's invasion of Kuwait stayed in the collective global memory as the picture of burning oil wells.
December 25, 1991	Mikhail Gorbachev's 12-minute speech on national television announcing that the Soviet Union would cease to exist. In his speech, Gorbachev made an indirect reference to the importance of energy for the success and security of a state: "We have a lot of everything – land, oil and gas and other natural resources…" (Yergin, 2011). The end of the Cold War introduced uncertainty into the geopolitics of energy.
March 20, 2003 to December 18, 2011	2nd Gulf War: The reality of the war and occupation of Iraq gave way to uncertainty, political insecurity and sectarian violence, which were followed by the offensive against the Islamic State after 2015 (https://www.bbc.com/news/world-middle-east-14546763).
August 23, 2005	Hurricane Katrina caused catastrophic damage in Florida and Louisiana. The importance of black swan type of natural disasters in the context of energy grids was made clear.
2005 to 2009	Gas crisis between Russia and Ukraine, with a detailed time line available at https://www.reuters.com/article/us-russia-ukraine-gas-timeline-sb-idUSTRE50A1A720090111. During the Ukrainian crises, there was significant concern in the European Union, which obtains much of its natural gas from Russia.
December 18, 2010	The Arab Spring upheaval changed the strategic balance in the Middle East and North Africa (MENA), with indirect implications for energy and geopolitics.
March 11, 2011	Fukushima Daiichi Nuclear Accident: The importance of securing energy installations from "unthinkable" natural threats (even unusual ones like tsunamis as opposed to earthquakes, and further to traditional threats like terrorist attacks) became dramatically obvious in a country (Japan) devoid of indigenous energy resources.
April 17 to 19, 2011	Major cyber attack on Sony compromised personal details from 77 million accounts and prevented users of PlayStation 3 and PlayStation Portable consoles from accessing the service (https://en.wikipedia.org/wiki/2011_PlayStation_Network_outage). Although this specific incident was not about energy, it brought to light the vulnerability to cyber attacks as a potential threat to energy security.
August 15, 2012	Cyber attack on 35,000 computers of Aramco, the Saudi Arabian oil company (https://www.nytimes.com/2012/10/24/business/global/cyberattack-on-saudi-oil-firm-disquiets-us.html), the biggest computer hack in history.

Date	Historical event
	Following the 2011 Sony incident, this cyber attack impacted a state oil company, Aramco, that supplied 10% of the global demand for oil (https://money.cnn.com/2015/08/05/technology/aramco-hack/index.html), alerting the world to the terrifying possibility of a cyber Pearl Harbor.
January 16-19, 2013	In Amenas gas plant hostage crisis in the Sahara desert in Algeria: As terrorists linked to Al-Qaeda attacked the Tigantourine gas facility near In Amenas, Algeria, executing at least 39 expat hostages (10 of them Japanese), (https://www.theguardian.com/world/2013/jan/25/in-amenas-timeline-siege-algeria). The world came into the alarming realization that terrorism constitutes a serious global threat to energy infrastructure and the power grid.
February 25, 2015	The EU Energy Union was adopted with the main task of creating a fully integrated internal energy market to enhancing energy security, improve energy efficiency, decarbonize the economy and support research and innovation (https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union). Further to the states objectives, the energy union of EU member states will allow the EU to negotiate better deals for Russian gas and be a more powerful geopolitical player.
July 14, 2015	The Joint Comprehensive Plan of Action (JCPOA), a nuclear deal between Iran, the five permanent members of the United Nations (US, UK, China, Russia, and France), Germany and the European Union, was announced. Per JCPOA, Iran agreed to limit its enrichment of uranium in exchange for the lifting of crippling sanctions. A full timeline is available at https://www.armscontrol.org/factsheet/Timeline-of-Nuclear-Diplomacy-With-Iran.
September 10, 2015	US House Energy & Power Subcommittee approved a bill to lift the 1975 oil export ban (instituted by EPCA), encouraging new investments and the creation of new jobs in all areas of the economy.
May 8, 2018	President Trump announced that he is withdrawing the United States from the Joint Comprehensive Plan of Action (JCPOA, Iran's nuclear deal) and signs a presidential memorandum to institute the "highest level" of economic sanctions on Iran (https://www.armscontrol.org/factsheet/Timeline-of-Nuclear-Diplomacy-With-Iran).
May 2019	Yemen's Shiite Houthi rebels attacked two Saudi pumping stations with armed drones. As in the case of the Algerian gas plant hostage crisis in the Sahara desert, this incident underscored the potential impact of terrorism as a new threat to energy security.
2020	The COVID-19 pandemic dramatically impacted energy markets, with both primary energy and carbon emissions falling at their fastest rates since World War II. The decline in global primary energy consumption and carbon emissions is the most significant fall since 1945 (BP Statistical

Date	Historical event
	Review, 2021).
February 2022	Full-blown global energy crisis following Russia’s invasion of Ukraine. The price of natural gas reached record highs, and as a result, so did electricity in some markets. Oil prices hit their highest level since 2008. The crisis involved all fossil fuels, while the 1970s price shocks were limited primarily to oil at a time when the global economy was much more dependent on oil and less dependent on gas (https://www.iea.org/topics/global-energy-crisis).
March & April 2022	Two EU emergency stock releases in March and April aimed at stabilizing the market following the Russian invasion of Ukraine. The low levels of emergency stocks in June 2022 reflected the two above releases, which were coordinated by the IEA and backed by several Member States. The levels of emergency stocks slightly recovered in July 2022 and were mainly composed of crude oil (45.5 mt in the EU), followed by gas/diesel oil (35.9 mt) and gasoline (9.8 mt) (https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20221018-2).
April 2023	OPEC+, which groups the 13 Organization of the Petroleum Exporting Countries with 10 other allies (including Russia), agreed to oil supply cuts to 3.66 million barrels per day (bpd), which helped push up prices above $86 per barrel (https://www.reuters.com/business/energy/goldman-sees-elevated-opec-pricing-power-100-per-barrel-by-april-2024-after-2023-04-04/).