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The future of geothermal energy in Europe

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Preface

I would like to thank the University of Gävle and to my professors in this Master's Programme, for the valuable knowledge and the opportunity to write this thesis, especially to Diogo Cabral.

All of this has been possible thanks to the support of my family and friends, who had not only encourage me in some difficult moments, but also provide their financial support. Special thanks to Javi, for listening, reading and for being always ready. Also to Juli, for being there, in spite of everything.

But the most special recognition to someone who takes care of everything for me, allowing me to be free to dedicate myself to what I want to do. To my mum, for always bringing coffee.

Abstract

In this paper it is investigated the role that geothermal energy could play in the energy mix, to meet new system requirements.

As any other source, geothermal energy harnessing implies a number of risks mainly related to induced seismicity and landslides, together with the release of as greenhouse gases and metal salts. Moreover, important barriers to its implementation still exist, mainly concerning financial aspects and drilling operations. As well, administrative status is uncertain and related investment in R&D negligible.

However, geothermal energy presents important advantages in relation to other energy sources, as its reliability and large capacity factor, comparable to nuclear and natural gas plants. It could help to reduce both the global warming, whose potential is up to 5 times lower than in the case of fossil fuels, and the landuse, the lowest of any power plant. Additionally, in spite of the high and risky initial investment, energy produced by geothermal means is amongst the cheapest.

The geothermal potential is large enough to substantially contribute to the energy mix, through locally available resources. Economic potential in Europe by 2050 is estimated in 100 – 4 000 TWh_e and 880–1 050 TWh_{th}.

Nevertheless, currently available technology strongly limits the access to geothermal resources. In addition, predictions about geothermal utilization are modest and have hardly been achieved to date. The key for the future is the development of the Engineered Geothermal Systems.

Keywords: Geothermal Energy, Opportunities, Risks, Barriers, Development scenarios, Status in Europe, Potential.

Nomenclature

Units of measure.

Unit	Description	Unit	Description
<i>Energy</i>		<i>Power</i>	
TJ	Terajoules	MW	Megawatts
EJ	Exajoules	MW _e	Megawatts of electric energy
PJ	Petajoules	MW _{th}	Megawatts of thermal energy
kWh	Kilowatts hour	GW	Gigawatts
kWh _e	Kilowatts hour of electric energy	GW _e	Gigawatts of electric energy
kWh _{th}	Kilowatts hour of thermal energy	GW _{th}	Gigawatts of thermal energy
MWh	Megawatts hour	<i>Mass</i>	
MWh _e	Megawatts hour of electric energy	g	Grams
MWh _{th}	Megawatts hour of thermal energy	kg	Kilograms
GWh	Gigawatts hour	TOE	Tonne of oil equivalent
GWh _e	Gigawatts hour of electric energy	gCO _{2eq}	Grams of CO ₂ equivalent
GWh _{th}	Gigawatts hour of thermal energy	kgCO _{2eq}	Grams of CO ₂ equivalent
TWh	Terawatts hours	gSO _{2eq}	Grams of SO ₂ equivalent
TWh _e	Terawatts hours of electric energy	g1.4DB _{eq}	Grams of 1.4 dichlorobenzene
TWh _{th}	Terawatts hours of thermal energy	gSB _{eq}	Grams antimony equivalent
<i>Distance</i>		<i>Temperature</i>	
cm	Centimetres	°C	Degrees Celsius
km	Kilometres	<i>Noise level</i>	
<i>Distance</i>		dB	Decibels
m ²	Square metres	<i>Currency</i>	
km ²	Square kilometres	€	Euro
<i>Volume</i>		<i>Other</i>	
m ³	Cubic meters	Δ	Variation

Abbreviations and acronyms.

Letters	Description
AC	Acidification
AD	Abiotic resources depletion
Avg	Average
ATES	Aquifer Thermal Energy Storage
BHE	Borehole heat exchanger
CAPEX	Capital expenditure
CHP	Cogeneration of heat and power
CSP	Concentrating Solar Power
DH	District heating
DHS	District heating system
EGS	Engineered geothermal systems
FAO	Food and Agriculture Organization of the United Nations
FiT	Feed-in tariff
Gas CC	Gas combined cycle
Gas GT	Gas simple turbine
GE	Geothermal energy
GeoDH	Geothermal District Heating
GHG	Greenhouse gas
GSHP	Ground-source heat pump
GW	Global warming
HDR	Hot dry rock
HP	Heat pump
HSA	Hot sedimentary aquifer
HT	Human toxicity
LCOE	Levelized cost of electricity
LCOH	Levelized cost of heat
Med	Medium
Mw	Moment magnitud
NREAP	National Renewable Energy Action Plan
O&M	Operation and maintenance cost
PMs	Particulates Matter
PTC	Parabolic trough collectors
R&D	Research and development
RD&D	Research, development and demonstration
SGE	Shallow Geothermal Energy
Solar PV	Solar photovoltaics
ST	Solar tower
TES	Total energy supply
UTES	Underground Thermal Energy Storage
yr	Year

<i>Organizations</i>	
EC	European Commission
EU	European Union
EU-27	Current EU countries, i.e. Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, The Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden.
EU-28	Former EU countries, i.e. EU-27 plus United Kingdom.
IEA	International Energy Agency
IGA	International Geothermal Association
IRENA	International Renewable Energy Agency

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1 Introduction

1.1 Background

The World's total energy supply (TES) in 2019 was $6.06 \cdot 10^8$ TJ [1]. Figure 1 shows the TES evolution between 1990 and 2019, which has grown steadily (at an average rate of 1.8% per year), increasing by more than 65% in this period [1]. By contrast, TES in Europe seems to follow a consolidated decreasing trend. In any case, global trend is expected to continue to grow, reaching a value of up to 275 % by 2050 [2].

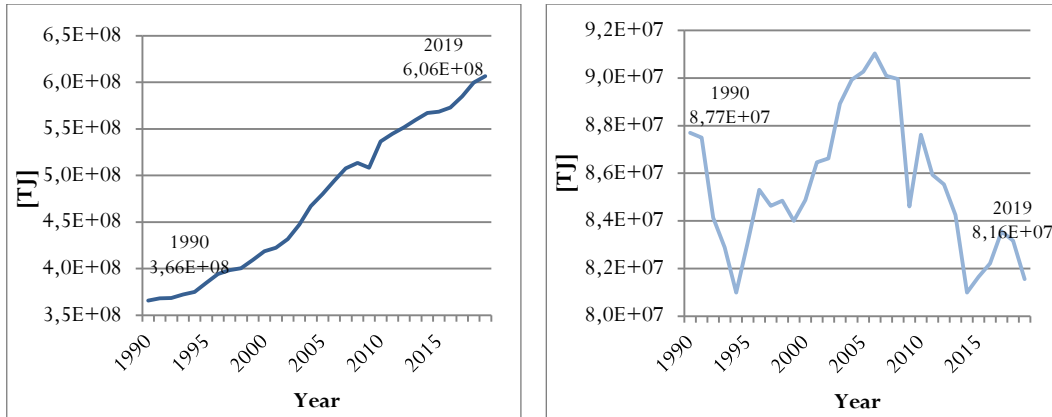


Figure 1. TES (TJ) evolution in worldwide and in Europe, between 1990 and 2019 [1].¹

Nowadays, the energy mix is still dominated by fossil fuels, not only globally, but also at European level, as can be seen in Fig. 2 [1]. The share of this type of fuels is about 80% and 70% respectively. Among other sources only biofuels and waste, as well as hydropower in Europe, represent a relevant share. This characteristic makes the energy market very volatile, highly dependent of imports/exports between producing and consuming countries and always subject to external factors, such as geopolitical decisions.

In a context of demographic growth, rising energy demand and scarcity of traditional fuels, restructuring of the energy system appears to be compelled. The development and implementation of alternative sources are the focus of many countries' efforts, aiming to achieving environmental goals, limiting related costs and imports dependency and assuring energy supplies.

The involvement of the European Union in the energy transition strategy aims to provide secure, sustainable, competitive and affordable energy, through energy efficiency improvements, the Paris Agreement accomplishment and supporting research and innovation in clean technologies [3].

¹ Full data in Table B - 1.

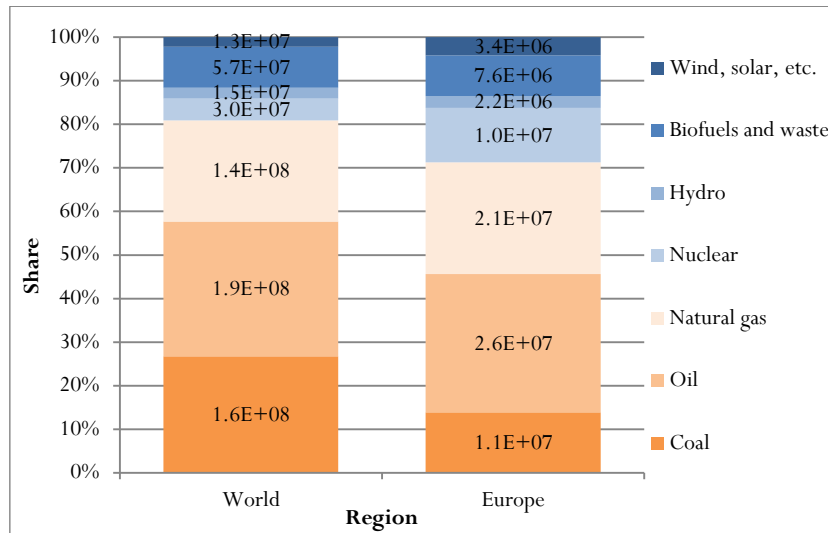


Figure 2. TES (TJ) by source in the World and in Europe, in 2019 [1].²

Among other clean sources, geothermal energy could be of great relevance and it may play a key role in the future of energy. Shortall & Uihlein [4] assumed the annual extractable geothermal energy worldwide to be $3.6 \cdot 10^8$ TJ, i.e. equivalent to 86% of the final energy consumption in 2019 [1]. However, its use in the same year was limited to 88 countries which utilized direct heat for different applications, such as building and greenhouse heating, bathing or food processing, for a total amount of $1.02 \cdot 10^6$ TJ [5]. Even smaller was the use for electricity generation, currently implemented in 30 countries and accounting for a total output of approximately $3.28 \cdot 10^5$ TJ [1], [6]. Figure 3 illustrates the countries currently using GE [7].

The TES fraction corresponding to Europe is approximately 13.5% ($8.2 \cdot 10^7$ TJ, 2019) and 10.8% ($6.6 \cdot 10^7$ TJ, 2019) if only the EU-28 is considered [1]. The usage of the different energy sources in Europe from 1990³ has not experienced major changes (apart from coal, whose reduction is appreciable), although the overall decreasing trend (see Fig. 2) [1].

² Full data in Table B - 2.

³ Full data in

Table B - 3.

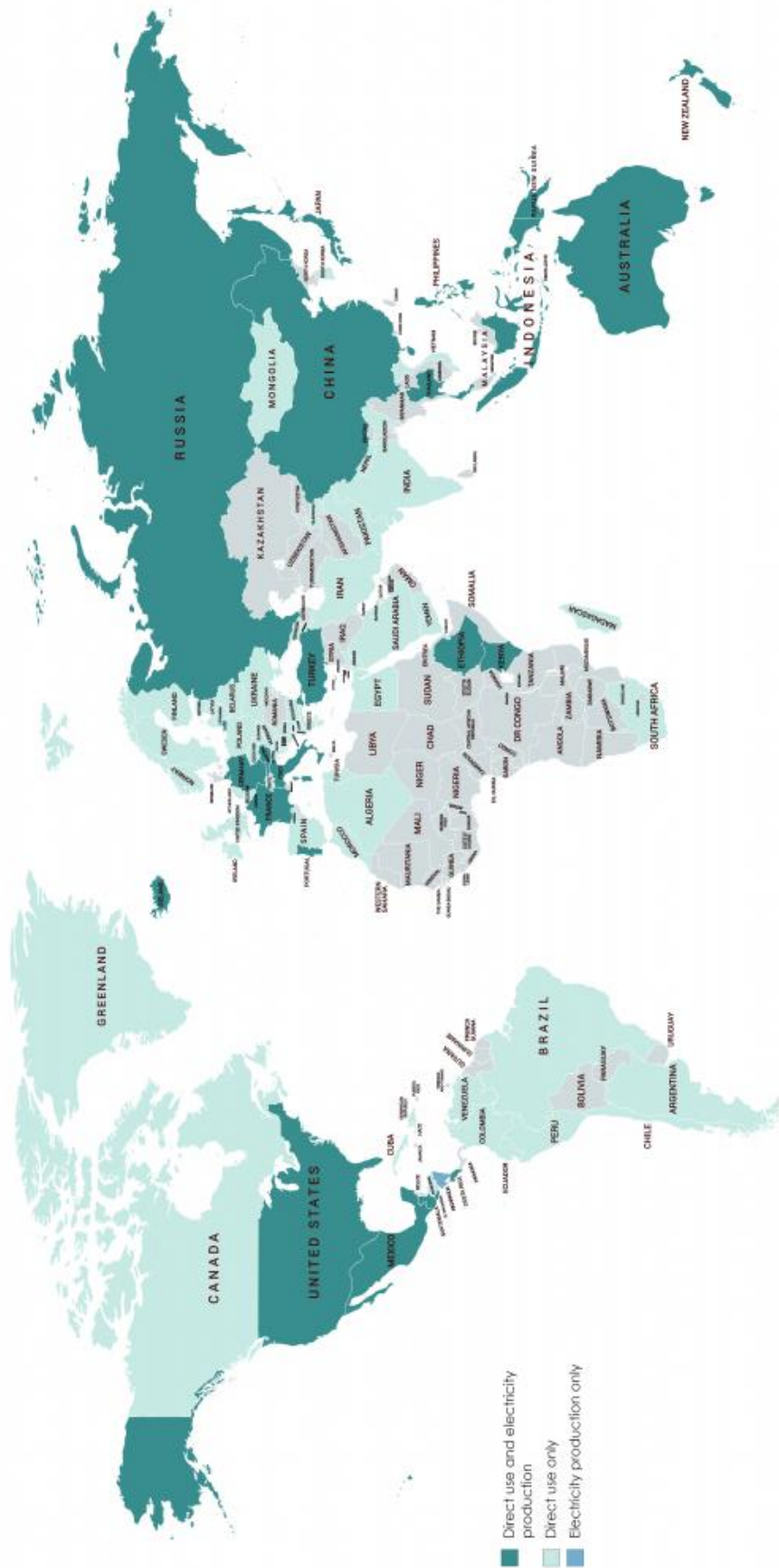


Figure 3. Geothermal Energy implementation in the World [7].

The same database includes GE in a varied group of minor sources, which represents a share of 2.2% worldwide, 4.1% in Europe and 3.9% in the EU-28 [1]. Specific quantities for GE are given when considering electricity and heat production, which are summarized in Table 1 [1]. GE represents in all cases less than 1% [1]. In contrast, natural gas and nuclear energy account for almost half of this market, followed by coal. The deployment of renewable energies has been conditioned by a number of constraints in favour of the aforementioned sources, as they are the traditionally high costs associated and the incapability to supply baseload energy.

Table 1. Electricity and heat generation by source in Europe and EU-28 in 2019 [1].

Source	Europe		EU-28	
	[TJ]	[%]	[TJ]	[%]
<i>Electricity generation by source</i>				
Nuclear	3 351 391	22.63	2 957 479	25.42
Natural gas	3 110 537	21.01	2 519 528	21.66
Coal	2 615 076	17.66	1 794 013	15.42
Hydro	2 360 437	15.94	1 270 642	10.92
Biofuel	646 366	4.37	627 750	5.40
Solar PV	543 251	3.67	478 631	4.11
Oil	201 240	1.36	192 352	1.65
Waste	187 042	1.26	176 548	1.52
Geothermal	78 106	0.53	24 214	0.21
Solar thermal	20 459	0.14	20 459	0.18
Tide	1 847	0.01	1 847	0.02
Other	24 224	0.16	17 716	0.15
Total	14 806 530	-	11 634 400	-
<i>Heat generation by source</i>				
Natural gas	1 401 488	43.37	865 620	36.01
Coal	635 329	19.66	556 692	23.16
Biofuels	601 988	18.63	526 637	21.91
Waste	278 104	8.61	251 914	10.48
Oil	82 691	2.56	69 475	2.89
Geothermal	45 984	1.42	12 945	0.54
Nuclear	11 401	0.35	3 980	0.17
Solar thermal	2 385	0.07	2 385	0.10
Other	171 974	5.32	114 356	4.76
Total	3 231 344	-	2 404 004	-

Geothermal energy can be defined as “*the energy contained as heat in the Earth’s interior*” [8]. It can be used both for electricity generation and for non-electricity purposes, that is heating and cooling [9], [10], to provide either base or flexible load energy [4]. It has been used in power plants for more than a century, but its direct use dates back several millennia⁴.

The most relevant application of direct-use geothermal energy is ground-source heat pumps (GSHPs), followed by bathing & swimming, space heating, greenhouse heating, aquaculture pond heating and industrial process heat [5]. Data since 1995⁵ show a significant increase in its use for space heating, bathing and swimming by means of GSHPs. It is noted that some European countries have significant contributions in this regard, such as Iceland, Sweden, Switzerland and Turkey [5]. Likewise, the cooling capacity of GSHPs could have a notable importance in the south of Europe [12].

The relevance of geothermal energy for industrial applications, reviewed by Focaccia et al. [13], is given by the high capacity factor and the opportunity to reduce the significant fraction that energy represents in this sector. Typical uses include winter heating, summer cooling and underground thermal energy storages. However, industry accounts for a small portion of geothermal direct-use, as the high temperatures needed in the process heat require medium enthalpy resources (90 - 150°C), of limited availability [13].

Applications are also related to agricultural and agroindustry sectors, as for crop drying, cultivation of spirulina or carbonation of soft drinks [5]. The Food and Agriculture Organization of the United Nations (FAO) presents the “Lindal diagram” (Fig. 4) to illustrate these potential uses [14].

Other uses include cover ground heating, raceway heating, agricultural crop drying, snow melting & space cooling, animal husbandry, etc [5].

⁴ For the more curious, the book written by Cataldi et al. [11], containing “*historical records and stories*” about the direct-use of geothermal energy around the globe, is recommended by Fridleifsson [2] and Lund & Toth [5].

⁵ See Figure B - 1.

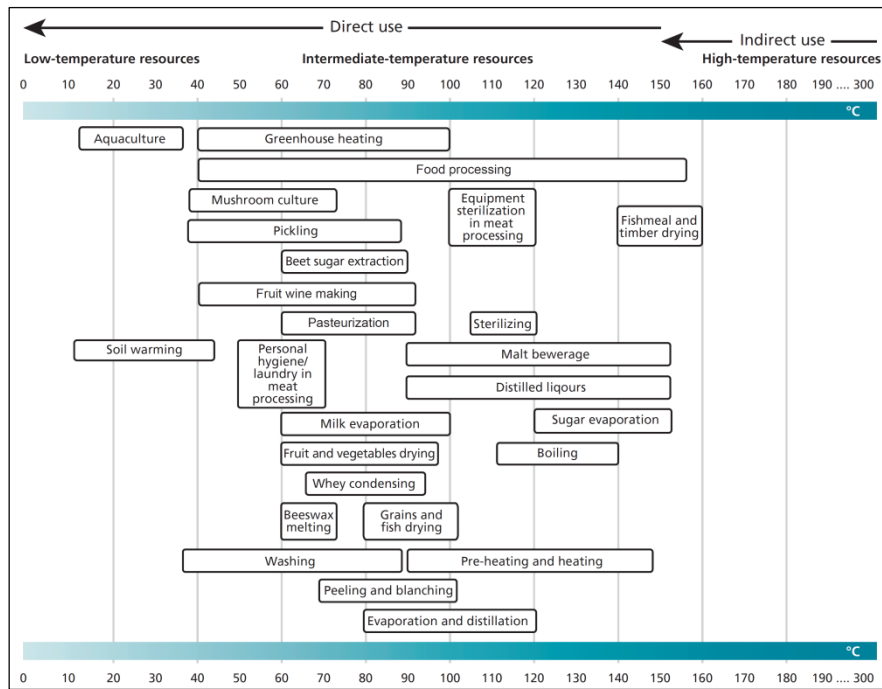


Figure 4. Lindal diagram of potential uses of geothermal energy in the agriculture and agro-industry sectors [14].

Cascade utilization⁶ of geothermal resources is a good opportunity to improve efficiency and thus, economics of those systems [4]. The fluid would be used initially for electricity production (generally requiring temperature sources above 150°C⁷ [10]) and then, in a second level, for cooling purposes [15]. Subsequently, it would be applied for progressively lower temperature heating applications (direct heat applications require temperatures between 10 and 150 °C [10]) [15]. The process would be completed with the reinjection [5].

GE can be similarly used in combined heat and power (CHP) generation. During the period 2015 - 2019 a total of 322 wells (12.2% of the World's total), were drilled by 18 European countries for this purpose [5]. As mentioned above, electricity production by geothermal resources is limited. The development and implementation of engineered geothermal systems (EGS) could be the key to the widespread use in Europe [16]. Supercritical fluids are also a point of interest since it would mean a higher productivity and could increase the interest in deeper and hotter wells. However, serious problems have been encountered when trying to work with supercritical fluids. Efforts in the exploration and modeling of reservoirs need to be boosted [17].

⁶ See Figure B - 2.

⁷ Some technologies allow electricity generation with resources of a temperature below 100°C.

New applications and technologies, as well as the exploitation of by-products, would also contribute to enhance the suitability and deployment of geothermal energy. The use of abandoned mines for geothermal applications has been explored by Menéndez et al. [18]. Karayel et al. [19] investigated the potential of geothermal energy for green hydrogen production in Turkey.

Geothermal energy development continues, with advances in technology, innovative applications and increasing interest. This paper discusses the reasons for focusing on the future of this emerging technology.

1.2 Aim

The aim of this project is to assess the future role of geothermal energy in Europe. In this regard, an information-set is presented, identifying the main features that will condition the path followed by GE. Such information includes a review of the opportunities and risks derived from the use of geothermal energy, as well as the main challenges and barriers that constitute an obstacle to its implementation. In addition, the potential and technological status is assessed.

The focus is mainly on deep geothermal energy, especially its use for electricity generation, as it appears to be more restricted, but consideration is also given to direct use.

2 Method

To meet the thesis aims, existing literature has been reviewed. Different databases⁸ have been consulted for the scientific article research, such as those accessible through the Library of the University of Gävle, like Academic Search Premier, Discovery, IEEE Xplore, Google Scholar and ScienceDirect.

Directories of different energy and geothermal institutions have also been valuable sources of data and reports including, for example, those of the International Energy Agency (IEA), International Renewable Energy Agency (IRENA), International Geothermal Association (IGA), ThinkGeoenergy, European Commission (EU) and GeoDH.

The terminology for the literature research, apart from the terms “geothermal energy” and “Europe”, include general aspects of the study in a first stage, as “shallow”, “deep”, “power generation”, “benefits”, “risks” or “challenges”. On a second stage, research words refer to more specific issues resulting from the first investigation, i.e. “environmental impact”, “costs”, “induced seismicity” or “drilling”.

Main limitations of the documentation reviewed are related to geography and time. The scope of the project is Europe. However, the territories considered may vary depending on the sources, i.e. they may refer to the geographical definition, the European Union, the Schengen area or include the Caucasian countries. Generally, overseas territories are excluded from the sources. The second main limitation is the updating of some data. Nevertheless, it is not intended to give an absolute figure, but rather a framework of background information to forecast a future situation. Therefore, these limitations are considered to have little impact on this analysis.

⁸ Links to different sources can be found in Table A - 1.

3 Results

3.1 Opportunities

Geothermal energy is described as a natural, sustainable and constant source of energy production [20]. Most relevant characteristics, making geothermal systems competitive, are reviewed below.

3.1.1 Versatility

Geothermal energy can be used both for baseload and flexible energy production [4], [9], [21]. This capability to generate baseload energy makes it especially relevant in comparison with other clean sources. Apart from oil and coal, only gas, biomass, nuclear and to some extent wave sources, can produce high reliable and constant energy, independently of climatologically or seasonal factors [22]. Mostly installed and developed technologies, as solar PV or wind turbines, only produce intermittent energy, very dependent of territorial and stationary weather conditions.

For this reason, natural gas and nuclear energy have become the main sources in electricity and heat production in Europe. Each of them represents more than 20% of the electricity share, while, for the latter, natural gas is responsible for 43% of the production. Nevertheless, associated constraints remain. In most European countries, natural gas use entails highly variable costs and dependence⁹, risking the security and reliability of the energy supply, for example as is currently happening as a consequence of the war in Ukraine. On the other hand, despite the considerable interest aroused by nuclear power in the last century, remaining reluctances to its use have led to a phaseout process in most European countries. However, their feasibility as baseload energy makes them difficult to replace.

The importance of geothermal energy would lie in this competitiveness with nuclear and gas, as it would be as reliable without the associated problems. Nevertheless, it has been reviewed that despite a theoretical potential large enough to supply the World's energy needs, the capacity recoverable with the currently available technology is significantly more modest.

⁹ The energy dependency rate of the EU-28 was 58% [23].

The capacity factor of geothermal energy for electricity production confirms the possibility to run it around the clock. In Table 2 the capacity factor of different energy sources used for electricity generation is compared [24], [25]. Geothermal energy capacity factor is comparable to fossil fuels, nuclear and bioenergy (in all cases over 80% on average). By contrast, renewable sources are below 50%, being as low as 16% in the case of solar PV.

Capacity factor for heat production follows similar trends. Values for geothermal energy¹⁰ (20 – 70%) are similar to biomass (25 – 80%) and above those of solar thermal (8 – 20%) [26].

Table 2. Capacity factors of different sources used for electricity generation [24], [25].

Source	Capacity factor [%]	Source	Capacity factor [%]
Nuclear	90	Coal	85
Gas CC	85	Gas GT	85
On-shore wind	36 (32 - 39)	Off-shore wind	44.2 (38 - 50)
Solar PV	16.1 (9.9 - 20.8)	CSP	42 (40 - 45)
Hydropower (large)	33 (16 - 59)	Hydropower (small)	44 (33 - 68)
Bioenergy	82 (48 - 92) Bagasse: 83 Landfill gas: 83 (83 - 91) Other vegetal and agricultural waste: 85 (78 - 91) Wood waste: 80 (62 - 89) Renewable municipal waste: 78 (64 - 89)	Geothermal	83 (76 - 91) Average: 60 High: >90 Direct steam: 85 Flash: 82 Binary: 78

3.1.2 Low environmental impact

Geothermal energy is assumed as a low environmental impact and greenhouse gasses (GHGs) emissions source [10], since it is virtually CO₂ and waste free [22]. The truth is that the exploitation of geothermal fields implies the release of a number of substances potentially hazardous, but in sufficiently low quantities to consider it a clean energy [27], [28], [29].

¹⁰ Lund & Toth [5] indicated specific capacity factor for various categories of direct-use. See Table B - 4.

The assessment of Gkousis et al. [30] showed how the global warming potential of geothermal energy is deeply conditioned by the type of technology used. Table 3 collects the findings of this study, showing that the GW potential of geothermal systems for electricity generation varies from 31.7 (EGS-binary) to 35.23 (dry steam) $\text{gCO}_{2\text{eq}}/\text{kWh}_e$ [30]. The average value for the use of deep heat is $46 \text{ gCO}_{2\text{eq}}/\text{kWh}_{\text{th}}$. When CHP systems are utilized, GW potential is reduced to $23.3 \text{ gCO}_{2\text{eq}}/\text{kWh}_e$ and $6.8 \text{ gCO}_{2\text{eq}}/\text{kWh}_{\text{th}}$.

Table 3. GW potential of geothermal energy technologies [30].

Technology	GW Average [$\text{gCO}_{2\text{eq}}/\text{kWh}$]	GW range [$\text{gCO}_{2\text{eq}}/\text{kWh}$]
Dry steam	350.23	11.4 – 850
Flash	158.52	3.9 – 1 040
Binary	49	5.7 – 97
EGS-binary	31.7	7.5 – 52
Deep heating	46	3.8 – 188
CHP power	23.3	5.8 – 58
CHP heat	6.8	2.3 – 11.6

A comparison of the GW potential of electricity generation by different sources is referenced in Table 4 [27]. Taking into account the variability existing when talking about “geothermal” in general and considering mean values, the GW potential of GE would be similar to other renewable sources and 4 – 5 times lower than fossil fuels. The use of GE for direct heat applications could save $2.86 \cdot 10^{-4}$ TOE of fuel if used for heat purposes through electricity conversion and $1.43 \cdot 10^{-4}$ TOE in the case of utilize burning systems [5].

Table 4. GHGs in the electricity production by different sources [27].

Source	GW potential [$\text{gCO}_{2\text{eq}}/\text{kWh}_e$]	Source	GW potential [$\text{gCO}_{2\text{eq}}/\text{kWh}_e$]
Hydropower	0 – 450	Coal	850 – 1 300
Solar	0 – 300	Oil	700 – 900
Wind	0 – 100	Natural gas	450 – 1 250
Geothermal	0 - 400		

It is worth to mention that emissions from geothermal power plants are the result of the natural venting out process through the earth [27], [28], [29], being the direct ones negligible [28]. Focusing on CO_2 , released quantities are highly variable, although the range can be set between 0 and $91 \text{ kgCO}_2/\text{MWh}$. The most pessimistic approach indicates up to $120 \text{ kgCO}_2/\text{MWh}$ on average, or even $740 \text{ kgCO}_2/\text{MWh}$ in particular conditions [28], [29].

Though, these emissions are 10 to 20 times lower than those of fossil fuel-fired plants and still below solar and biomass [28]. Likewise, CO₂ levels in volcanic terrains are similar with or without geothermal field development [27].

GE utilization can also cause surface disturbances due to exploration, drilling and construction operation, but it is mostly temporally [27], [29]. Permanent land use of a geothermal power plant would range between 1.26 – 7.46 km²/MW [28], 8 times lower than a nuclear power plant, 12 times lower than a wind farm and up to 52 times lower than a solar PV [28]¹¹. In the case of Larderello complex, the land utilization is as low as 0.42 km²/MW [28].

Location of geothermal plant is often a delicate issue. Suitable sites are frequently found in unique areas, sometimes fragile, of high environmental value, outstanding because of their characteristic ecosystems, beauty, tourist attractive, historic interest, scenery, etc. [27], [28], [29]. The implementation of GE infrastructures creates a risk of deterioration or even disappearance¹². By contrast, introduction of geothermal installations in such environments could be beneficial from other approaches. Thus, this question must be deeply assessed¹³.

3.1.3 Availability

Shallow geothermal energy (SGE) is available everywhere, as well as, virtually, deep geothermal energy [4], [9], but in the reality limitations exists. That is to say, human capabilities to exploit this source do not allow to generalize its utilization, limiting it to locations suitable to current technology development. However, without the technological constraint, GE could theoretically be exploitable anywhere on Earth.

¹¹ Full data in Table B - 7.

¹² That is the case of New Zealand, where more than 100 geysers disappeared [28].

¹³ In the case of Kenya, for example, where 16 plants are installed in the surroundings of the lake Naivasha, living standards have been improved thanks to food security, water pumps for irrigation and drinking and greenhouses to eliminate famine [28]. On the other hand, it should be considered the impact of the environment modification over the indigenous Maasai community [29].

Parameters identified as most correlated to suitable geothermal sites are carbon dioxide, earthquake density, elevation/depth, global heat flow, sediment thickness, and surface air temperature [20], being the highest potential found in volcanic areas [9]. But these parameters have to be assessed considering that currently deep geothermal energy is strongly conditioned by the existence of hydrothermal reservoirs, of enough enthalpy for the purpose and at a reachable depth with available drilling techniques¹⁴. Thus, deep geothermal energy availability is fairly restricted.

Developments advanced enough to extend geothermal technologies to less limited fields could have a significant impact in remote, small and isolated territories. That would be the case of European overseas territories. The Azores islands, located in the middle of the Atlantic Ocean, 1 400 km away from Portugal mainland, have a geothermal power tradition of more than 40 years. About 24%, the second largest share, of the electricity requirements are covered with geothermal resources. In São Miguel island geothermal contribution to self-sufficiency accounts for a 44% [32]. In the case of France, 100 MW_e geothermal are expected to be installed by 2030¹⁵ in the French Overseas Territories, contributing to their independency [33].

3.1.4 Costs

Geothermal energy is a capital-intensive industry, only comparable to concentrated solar and nuclear. However, operating and maintenance costs are low and predictable [5], [9], [21]. The result is that despite the high upfront costs, electricity produced from geothermal is one of the cheapest and economic attractive in all forms [21].

¹⁴ The alternative is to use EGS, which will be later reviewed. Nowadays, these systems are poorly implemented and require development. Therefore, today's deep geothermal energy is this way constrained.

¹⁵ Nowadays, two geothermal power plants are running in France, one of those in France mainland (the experimental EGS project of Soult-sous-Forêts). The other one, Bouillante power plant is located in Guadeloupe Island (Caribbean). It has two units, dating back from 1996 and 2004, with a total installed capacity of 15.7 MW. The addition of two new units is under development. Besides, some investigation requests and exploration works have focused in Martinique and Reunion islands. Nonetheless, 2030 perspectives for the Overseas Territories seem difficult to accomplish.

Overall, the use of geothermal energy can be categorised as beneficial from an economic point of view. Mostly feasible business is the utilization of low-moderate temperature resources, which represents “*a significant contribution to a country’s or region’s energy mix*” [5]. Nevertheless, the exploitation of large steam reservoirs entailing greater costs, preferably “traditional” ones but not dismissing EGS, have positive results, as well. Even small hot water aquifers are competitive regarding other renewable energies [21].

The breakdown cost of the development of a geothermal project is shown in Table 5 [34]. According to it, those costs are strongly conditioned by the construction phase, which accounts for 45% of the total investment, followed by drilling operations, with a share of 37% [34]. That is consistent with the estimations of IRENA [9]¹⁶.

Table 5. Indicative cost for geothermal development of a 50 MW_e plant [34].

Phase / Activity		Low	Med	High	Share
		[€ ¹⁷ million]			[%]
1	Preliminary Survey, Permits, Market Analysis	0.95	1.89	4.73	0.7–1.8
2	Exploration	1.89	2.84	3.79	1.4–1.5
3	Test Drillings, Well Testing, Reservoir Evaluation	10.41	17.04	28.40	7.7–10.9
4	Feasibility Study, Project Planning, Funding, Contracts, Insurances, etc.	4.73	6.63	9.47	3.5–3.6
5	Drillings (20 boreholes)	42.60	66.27	94.67	31.7–36.5
6	Construction (power plant, cooling, infrastructure, etc.)	61.54	71.01	89.94	45.8–34.7
	Steam Gathering System and Substation, Connection to Grid (transmission)	9.47	15.15	20.83	7.0–8.0
7	Start-up and Commissioning	2.84	4.73	7.57	2.1–2.9
Total		134.44	185.56	259.41	Avg 193
In € Million per MW Installed		2.65	3.69	5.21	Avg 3.88

¹⁶ See Table B - 8.

¹⁷ Chosen currency in the present document is €. Those values expressed in other currency in the sources has been converted utilizing the exchange rate indicate by the European Central Bank (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/index.en.html) the day of the consultation.

The final cost of a geothermal power plant will be subject to the installed technology, as reveals Fig. 5, which represents the levelized cost of electricity (LCOE) of geothermal projects by technology type [24]. Binary systems seem to be more expensive than flash type and dry steam plants. But it is worth to mention that in all cases costs are within the range of fossil fuel plants, or even below.

In addition, the EC forecasts a significant reduction in the capital expenditure¹⁸ of both flash and binary power plants [9], whose major advantage is that allow the utilization low temperature resources [35]. During the next decades a constant reduction is expected until the amounts expected by 2050, which are up to € 1 360/kW for flash plants and between 1 771 and 2 123 €/kW for binary ones.

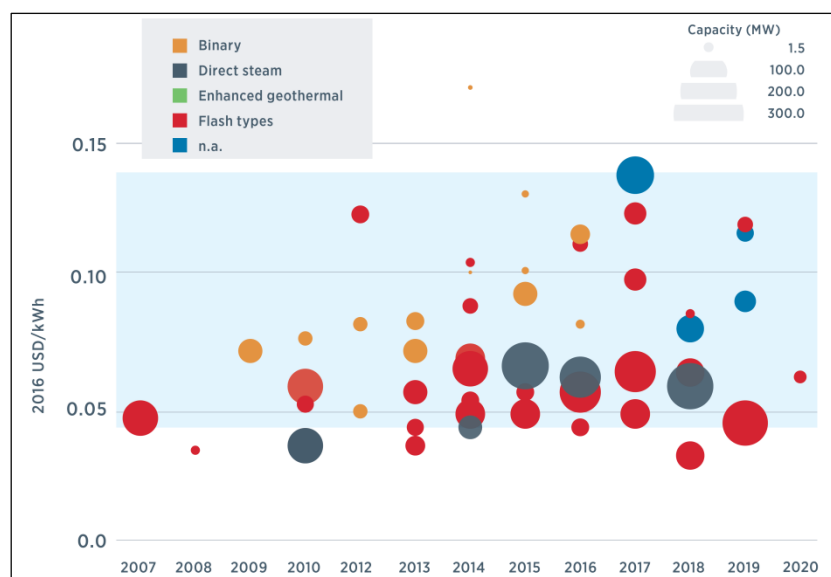


Figure 5. Geothermal project-level LCOE by technology, 2007-2020 [24].

The result is a levelized electricity cost of about € 0.067/kWh. Table 6 summarizes the capital expenditure (CAPEX), operation and maintenance (O&M) and LCOE from different sources, revealing that GE costs is competitive with all other sources [24], [26], [36].

Geothermal energy CAPEX is the one of highest, only below nuclear plant and concentrating solar power (CSP). Operation and maintenance costs are high if compared with other renewables (as solar ones) but on the average, if all sources are considered. In comparison with those suitable for baseload production, O&M are similar to coal and biomass plants, the double of gas, but half of the nuclear.

¹⁸ See Figure B - 3.

Figure 6 presents the LCOE produced with geothermal by technology and project size [24]. In this case, the value is not conditioned by the type of plant, but is mainly connected to the size. Except some specific cases, smaller plants tend to have higher electricity costs. But in all cases, LCOE is within or below the reference fossil fuel cost range set by the authors (€ 0.047 - 0.168/kWh). In addition, the deployment of EGS could reduce LCOE by 70% [37], as well as the exploitation of by-products [9].

Mention should be made of the fact that the payback period for geothermal energy (5.7 yr) is longer than of most renewable sources, as well as that of coal (3.2 yr), but shorter than that of gas plants (7 yr) [28].

Table 6. Reference CAPEX, O&M and LCOE [24], [25], [36].

Energy	CAPEX [€/kW]	O&M [€/kW/yr]	Elec. Price [€/kW]
Coal	3 429 (1 015 – 5 870)	108 (43 - 173)	0.085 (0.043 - 0.099)
Gas CC	994 (637 – 1 309)	35 (31 - 57)	0.090 (0.089 - 0.101)
Gas GT	767 (507 - 899)	49 (31 - 57)	0.093 (0.047 – 0.095)
Nuclear	6 406 (2 655 – 11 550)	253 (134 - 415)	0.065 (0.049 - 0.081)
On-shore wind	1 434 (1 111 – 1 954)	44 (40 – 48)	0.049 (0.033 - 0.062)
Off-shore wind	3 394 (2 267 – 5 529)	66 - 122	0.079 (0.062 - 0.124)
Solar photovoltaic	Residential: 1 726 (1 284 – 2 382)	9	Residential: 0.151 (0.098 - 0.223)
	Commercial: 1 125 (804 – 1 463)		Commercial: 0.110 (0.071 - 0.169)
CSP	4 337 (4 066 – 4 880)	PTC: 0.024 (0.017 – 0.030)	0.173
		ST: 0.021 (0.015 – 0.026)	0.072 - 0.102
Hydropower	Large: 1 840	19 - 57	Large: 0.114 (0.057 – 0.026)
	Small: 3 381		Small: 0.123 (0.093 – 0.202)
Marine power	4 734	-	0.322 – 0.360
Bioenergy	2 408 (566 – 7 517)	47 - 145 (23 – 301)	0.083 0.079 – 0.143
Geothermal	4 230 (2 651 – 5 491)	109	0.059 (0.044 – 0.089)

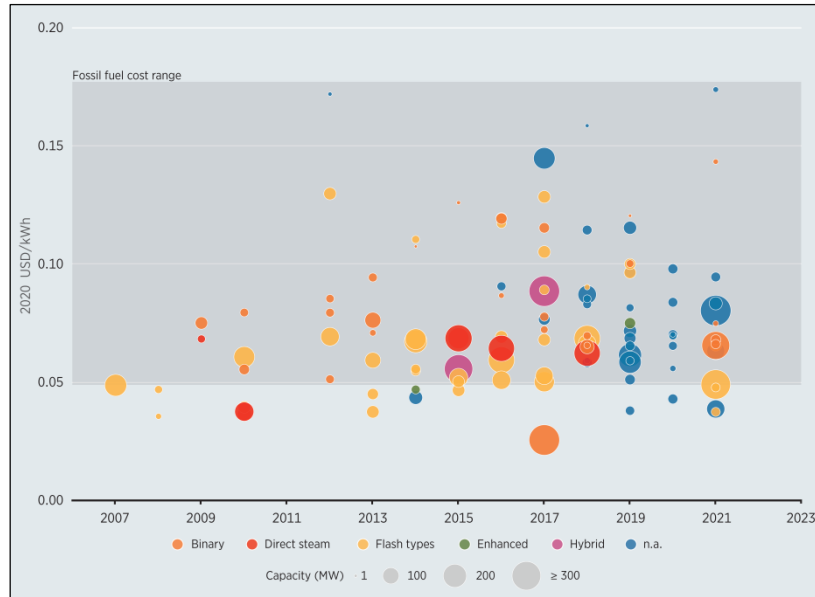


Figure 6. LCOE of geothermal power projects by technology and project size, 2007 – 2021 [24].

In relation to the levelized cost of heat (LCOH), information is very limited and restricted to domestic uses. IRENA [24] reports a cost of € 387/kW of DH scale solar heat, which leads to a LCOH of € 0.043/kWh. The average CAPEX in industrial and agricultural geothermal systems¹⁹ would be around € 104/PJ/yr, with an expected reduction to € 102/PJ/yr by 2050 [38]. At user level, Table 7 provides approximate costs of different domestic systems [1], [26], [36]. Values must be considered as a mere reference, but not as fact. According to them, geothermal heat utilization would remain among the cheapest source of heat, with capital costs in the same order than other renewable systems.

Table 7. Reference installed cost, operation & maintenance and levelized heat costs [1], [26], [36].

Energy	Capital cost [€/kW]	Heat price [€/kWh]
Biomass	101 – 947	0.009 – 0.047
Solar thermal combi system	2 367 - 5 681	0.104
Solar thermal water heater		0.019 – 0.189
Wood pellet	201 - 601	0.045 – 0.194
Gas boiler condensing	100 – 175	0.127
Gas boiler non-condensing	100 - 175	0.180
Electric air-air HP	-	0.114
Electric air-water HP	-	0.123
Electric ground-source HP	-	0.075
GSHP	752 – 2 003	0.084 – 0.142
Geothermal	289 – 1 894	0.005 – 0.047

¹⁹ Full data in Table B - 9.

3.1.5 Potential

Aghahosseini & Breyer [35] stated that “*full potential of geothermal energy has not yet been assessed*”, despite several investigations and models have been developed. However, hydrogeological information availability is limited and diffuse, especially at great depths [16] and the number of test boreholes limited.

The total Earth’s heat content would be about 10^{13} EJ and over 10^9 years would be required to exhaust it [39]. The amount corresponding the upper 10 km of Earth’s crust would be $1.3 \cdot 10^9$ EJ, enough to supply global energy consumption (600 EJ/yr) for 217 million years [37].

Technical potential production of GE would be almost 66% of the total offered by the “renewable” sources, becoming the most relevant of those, and more than three times greater than the next one, as depicts Table 8 [2].

Table 8. Technical potential of renewable energy sources [2].

Source	[EJ/yr]
Hydropower	50
Biomass	276
Solar energy	1 575
Wind energy	640
Geothermal energy	5 000
Total	7 600

According to Stefansson [40] the World’s geothermal potential would range between 50 - 2 000 GW_e for power generation and between 1 000 – $4.4 \cdot 10^5$ GW_{th} for direct heat. Among the identified resources, only 32% of them would be of a temperature higher than 130°C, and a fraction of 39% of the power potential is identified to be focused in 8 countries²⁰, of which only two are European.

A preliminary estimation of the geothermal potential for electricity and direct use in each European country is presented in Table 9 [41]. According to it, total values would be about 179 518 GWh_{th} and 78 304 GWh_e. Notwithstanding, differences between countries would be significant. Some of them present clear opportunities, such as Iceland, Turkey and Hungary.

²⁰ i.e. Iceland, Italy, USA, Indonesia, Philippines, Japan, Mexico and New Zealand [40].

Table 9. Geothermal energy potential [41].

Country	Potential electricity [GWh _e]	Potential direct-use [GWh _{th}]
Austria	400	7 700
Belgium	800	8
Bulgaria	1 600	3 850
Croatia	384	7 700
Cyprus	80	50
Czech Republic	0	770
Denmark	0	0
Finland	0	0
France	800	1 540
Germany	1 600	38 500
Greece	3 600	3 850
Hungary	3 040	15 400
Iceland	48 000	50 000
Ireland	0	100
Italy	8 000	3 850
Latvia	0	385
Lithuania	0	385
Macedonia	-	-
The Netherlands	80	2 310
Portugal	1 600	770
Rumania	1 600	15 400
Russia	-	-
Serbia	-	-
Slovakia	800	7 700
Spain	0	0
Sweden	0	0
Switzerland	-	-
Turkey	5 920	19 250
Total	78 304	172 588

Others stand out for one of the applications. After Iceland, Italy would account the biggest electricity potential, while in terms of direct use it would be Germany. A third group would be formed by countries with reduced or non-existent potential, as for example Denmark, Sweden or Spain.

However, those forecasts seem to be quite pessimistic in comparison to other models. For example, in the case of Spain, resources of a temperature higher than 150°C within 3-10 km depth, suitable for EGS utilization, would be up to 600 GW_e [42]. Resources between 150 and 200 °C would be found at 5 500 km in half of the country's territory [42].

The EGS potential in Europe was assessed by Chamorro et al. [42]. The study concluded that it would be as large as 6 560 GW_e (with temperatures higher 150°C and depths between 3 and 10 km). However, the sustainable potential would be 200 times lower, so a more realistic approach would indicate a capacity of 35 GW_e.

Similarly, technical potential is limited if the economic considerations are given. The assessment of the EGS in Europe conducted by Limberger et al. [43]²¹ indicated an economic²² capacity of 19 GW_e by 2020, 22 GW_e by 2030 and 522 GW_e by for 2050.

This forecast is consistent with that of the GeoElec study [16], which concludes that economic electricity potential in Europe would be 144 TWh by 2020, 171 TWh by 2030 and 4 000 TWh by 2050. Corresponding values for the EU-28 would be 21.2 TWh, 34 TWh and 2 570 TWh respectively [16].

Another study, conducted by Dalla Longa et al. [38] estimated the long-term economic potential for different applications. Results are illustrated in Fig. 7 [59]. It indicates that resources suitable for direct use can be extensively found at depths from 0.2 km.

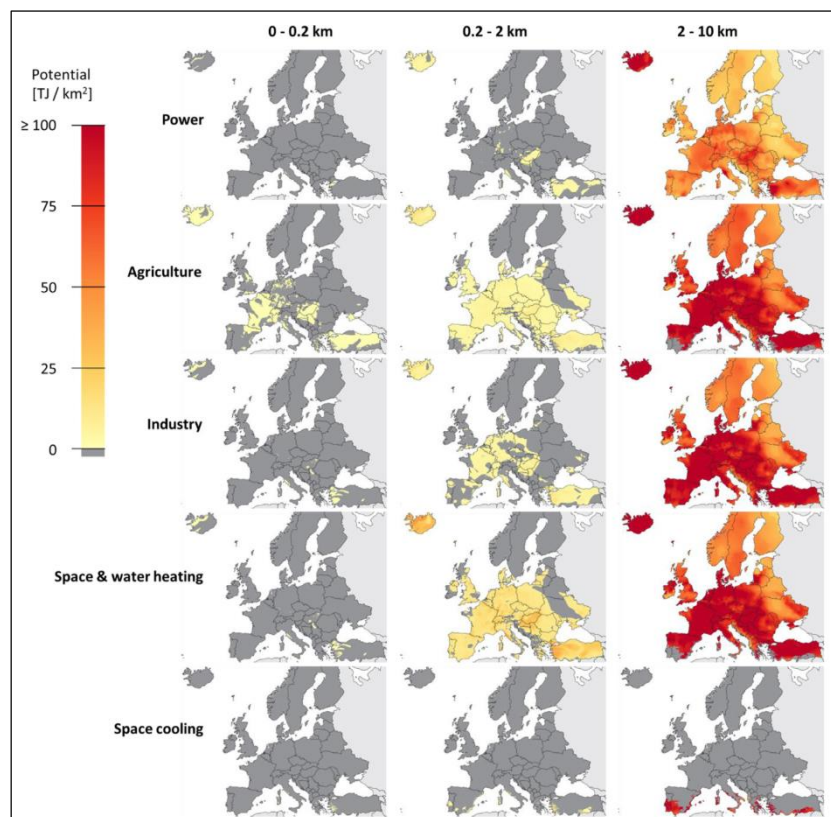


Figure 7. Long-term economic potential for various geothermal applications in Europe at different depths [38].

²¹ Full data in

Table B - 6.

²² LCOE in 2020: € 200/MWh; in 2030: € 150/MWh; in 2050: € 100/MWh [43].

At depths greater than 2 km, potential for power generation and direct use applications exist in all European countries. High production opportunities are identified specially in the central region, with capacities over 75 TJ/km². Space cooling possibilities are also reflected in the last map, for the Mediterranean region. Authors forecasted that geothermal heat generation could reach 3 300 – 3 800 TWh/yr by 2050, depending on the climate change policies and EGS development. Again, the development of EGS is highlighted. However, this technology is not yet widespread available, so the potential would rather focus on naturally existing hydrothermal reservoirs.

This is considered by Limberger et al. [44], who studied deep aquifers suitable for direct heat utilization. This type of reservoir underlies 16% of the earth's surface, representing a theoretical potential between 0.4 and 5·10⁶ EJ. The results are presented in several maps, whose extracts corresponding to the European territory are represented in Fig. 8, indicating relevant opportunities, mainly in the central region [44].

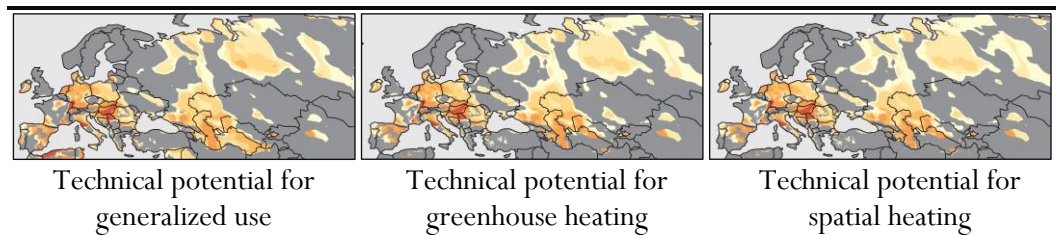


Figure 8. Technical potential of deep aquifers for different applications [44].

One of the main direct uses of GE is space & water heating and space cooling through district heating systems. The GeoDH Project, launched to promote its development, revealed that it can be implemented in all EU countries at competitive costs. More than a quarter of the population lives in areas directly suitable for geothermal DH and offers the opportunity to supply cooling in Southern countries.

Table 10 summarizes the share of population that could be benefited of the utilization of the technology [45]. Among listed countries [45], half of them could supply more than half of their population with geothermal district heating (DH). In the case of Denmark and Hungary, the reachable population could be up to 75 and 90% respectively.

Table 10. GeoDH potential in Europe [45]

Country	Population that could be reached with GeoDH
Bulgaria	50 %
Czech Republic	10 %
Denmark	75 %
France	37 %
Germany	50 %
Hungary	90 %
Ireland	35 %
Italy	50 %
The Netherlands	30 %
Poland	10 %
Romania	20 %
Slovakia	50 %
Slovenia	50 %
United Kingdom	20 %
Total	41 %

3.2 Risks

As in the case of any other source, the use of geothermal energy involves a number of risks and drawbacks. From a technical approach, the risk of depletion requires careful evaluation. But the most relevant for the society are the induced seismicity and environmental impact. Therefore, they need to be taken into account in geothermal projects, as they could disrupt their development. The most relevant ones are reviewed below.

3.2.1 Renewability

Apart from the fact that several experts consider geothermal a renewable resource (and this is often mentioned in its definition), due to its virtually inexhaustibility consequence of the heat nature [4], [10], [22], depletion or even deterioration of the reservoir due to excessive production is pointed as a major risk in geothermal exploitation [35]. Renewability depends on the extraction rate, which is generally faster than that of replacement, depending on several factors [10]. The reason is that sustainable exploitation of reservoir may result in uneconomic systems and long payback periods [39]. In the case of deep reservoirs, the injection required to avoid depletion can simultaneously cause a temperature decline. But the balanced withdrawal rate is often not economically achievable [39].

Blank et al. [46] pointed out that spatio-temporal evolution of the cooling front emanating from the injection wells must be taken care of to ensure the sustainability of the resource. This could be achieved by establishing a “dynamic recovery” equilibrium or establishing moderate production rates with multiple wells [22]. Hot dry rock (HDR)/EGS systems demonstrate than moderate production rates secure the reservoir longevity, with similar total energy yields [39]. Similarly, the sustainability of shallow system will be subject to the hydrogeological site-conditions and dependent on the design itself. In shallower cases (GHP horizontal systems or groundwater coupled GSPs) sustainability is guaranteed by the particular conditions [39]²³.

3.2.2 Induced seismicity

“Induced seismicity is recognised as a possible hazard in practically all engineering endeavours where stress or pore pressure in the subsurface is altered” [47]. Induced seismicity derived from the exploitation of geothermal resources is a major risk, of high social relevance.

Grünthal [48] evaluated the affection of this kind of events. The study compared geothermal related seismicity with other human-induced events²⁴ and natural occurring earthquakes. Observed area corresponded to west Central Europe²⁵. The study showed 33 events geothermal-related of a moment magnitude (Mw) higher of $M_w \geq 2.3$ in the period between 2003 and 2010.

In Fig. 9 can be observed that the maximum magnitude event due to GE was the lowest of all considered inducers, with a value of $M_w = 3.2$, being classified as *“moderate, with a few cases of weakest non-structural damage”* and less than a half of the maximum recorded ($M_w = 6.6$ due to tectonic earthquakes) [48].

The study also considered that induced seismicity due to the underground construction works is a minor issue, and thus not assessed [48]. It could be concluded that the magnitude of seismic events induced by geothermal projects is low and below the levels related to other activities. However, the risk exists, together with social concerns, which are in any case understandable.

²³ A summary of main features conditioning sustainability of geothermal systems can be found in Table B - 10.

²⁴ The study includes mining or exploitation of coal, rock salt and potash, hydrocarbons and ores [48].

²⁵ i.e. Germany, Luxembourg, and adjacent parts of Poland, Czech Republic, Austria, Switzerland, France, Belgium and The Netherlands [48].

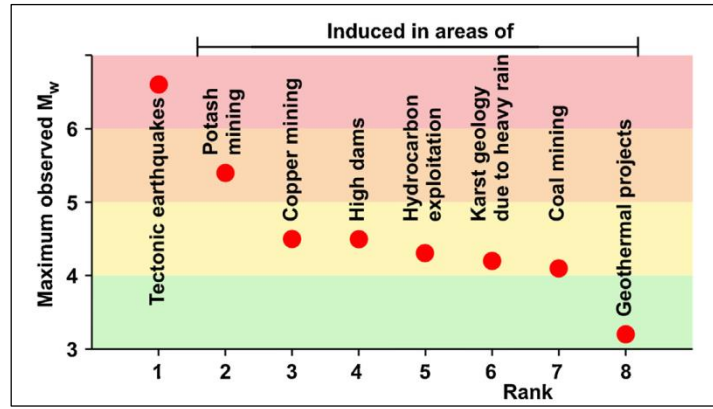


Figure 9. Ranking of maximum observed magnitudes for different sources of seismicity in Central Europe [48].

3.2.3 Environmental hazards

Although geothermal energy is considered as a clean source [27], whose environmental benefits have been previously reviewed, some related hazards need to be addressed.

Environmental effects vary considerably depending on site-specific geological conditions (reservoir depth, the geofluid temperature and composition and the rock formations) and technological aspects (energy conversion technology, production flow, plant capacity, capacity factor and lifetime) [27], [30]. Most relevant harms related to GE are global warming (GW)²⁶, acidification (AC), human toxicity (HT), freshwater ecotoxicity, abiotic resources depletion (AD) from ultimate reserves, cumulative energy demand fossil or non-renewable and water consumption (resource depletion) [30]²⁷.

The exploitation of geothermal resources releases a number of gases (CO_2 , H_2S , NH_3 and CH_4)²⁸ and metal salts (mercury, boron, arsenic, cadmium, aluminium, etc.) than might cause damage to the atmosphere, soil and ponds [27], [28], [29]. Major concerns are related to methane and hydrogen sulphide. CH_4 emissions would be in the order of 0.80 g/kW, in spite of being seldom in the focus. H_2S could represent up to 90% of the NCG in geothermal fluids. The risk comes with its oxidation and precipitation in form of SO_2 , contributing to acid rains [27], [29].

²⁶ Global warming potential of geothermal extraction has been reviewed in section 3.1.2.

²⁷ Key findings are summarized in Table B - 11.

²⁸ Reference values are given in Table B - 12.

Apart from induced seismicity, geological hazards would include slumps, landslides²⁹ and subsidence, resulting from the loss of pressure below the crust. Most striking case of subsidence is that of Wairakei field (New Zealand), which reached a magnitude of 15 m. In Europe, the Larderello field (Italy) current subsidence rate is 25 cm/yr. Additionally, reinjection may cause swelling and, in extraordinary conditions, hydrothermal explosions and well blow-out may occur [28], [29].

Heat rejection can also create an environmental damage. The low efficiency of geothermal power plants (12% on average [48]) leads to heat rejections rates (MW_{th}/MW_e) of about 4.8 in flash type and direct steam plants and up to 9 in binary systems, when all other sources ranges between 1 and 3 [28], [29].

Cogeneration and cascade utilization systems may be a good solution to mitigate this impact [28], although reinjection is currently the most likely technique to address this issue [27]. Reinjection also allows to avoid undesirable side effects of lowering the groundwater table [27].

In addition, concerns exist about noise derived from geothermal use. During the drilling phase, noise levels up to 120 dB could occur [27]. Once the plant is in operation, noises derived from engines, turbines and cooling tower can be around 45 – 83 dB [28]. Measures can be put in place to keep noise below 65 dB [27].

²⁹ In 1991, a landslide of a volume of 800 000 m³ in the field of Zuni I (Guatemala) result in 23 people killed [29].

3.3 Technology

Geothermal energy technology, considered feasible [10] can be classified according to Fig. 10³⁰ [4].

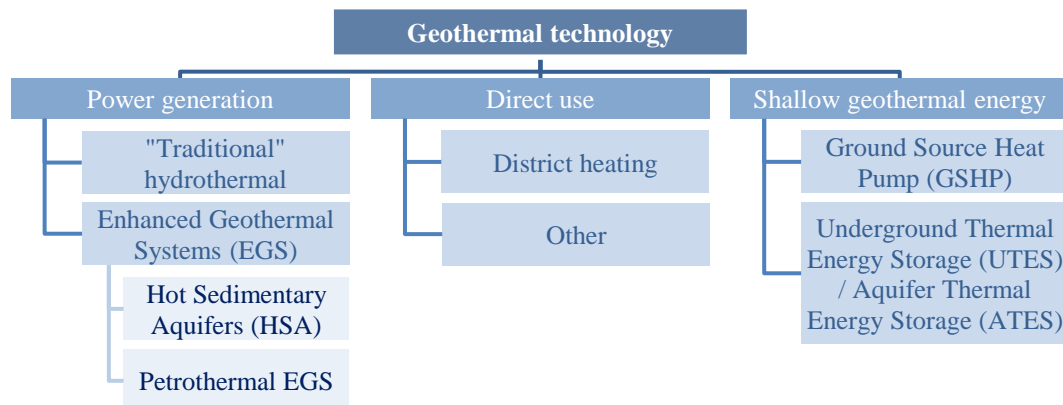


Figure 10. Classification of geothermal technology [4].

3.3.1 Power generation

Power generation with GE requires source temperatures higher than 150°C [35], in spite of some technologies have allowed to lower this temperature below 100°C [16]. To meet this condition, the presence of fluid at high depths is necessary, as it is the case of natural hydrothermal reservoirs.

Technology used in traditional plants can be considered as mature and commercially proven, with still some room for improvement [4]. But high enthalpy resources (>180°C) are quite limited within Europe, having hot sedimentary aquifers (HSA) more widespread occurrence than natural hydrothermal reservoirs [4]. Additionally, current systems in operation work with well depths up to 4 km depth [4], limiting the extraction opportunities. The importance of the EGS lies in these facts.

With this technology, fluid is injected into the subsurface in a suitable location, both for HSA and petrothermal systems [4], reaching depths up to 10 km [4], and thus growing the amount of energy capable to be extracted.

Despite EGS is a breakthrough technology proven [4], [16], it is not implemented, neither can be defined as mature, and many challenges remain [21]. EGS pilot projects are conducted in the plants of Soultz-sous-Forêts and Strasbourg, in France; as in the United States [9], [37]. But high costs and risks of this technology need to be mitigated to make EGS a reality [4].

³⁰ Brief description of the technologies is given in Figure B - 4.

Five technologies are used in GE power plants: dry steam, single flash, double flash, binary (Organic Rankine – Kalina Cycle) and advance geothermal energy conversion systems (hybrid single-double-flash systems - triple flash, hybrid flash-binary systems, hybrid fossil-geothermal systems, hybrid other-renewable heat source-geothermal systems, and hybrid back pressure system). A simpler classification would distinguish between steam cycles for higher well enthalpies and binary cycles for lower enthalpies [10].

Current worldwide installed capacity is summarized in Fig. 11³¹, considering the region and type [50-62]. A share of 24% corresponds to Europe. Mainstream technology employed in the geothermal power generation is single flash. However, in Europe 39% of the capacity is in form of binary plants, the second on importance worldwide. Triple flash and back pressure plants are very few.

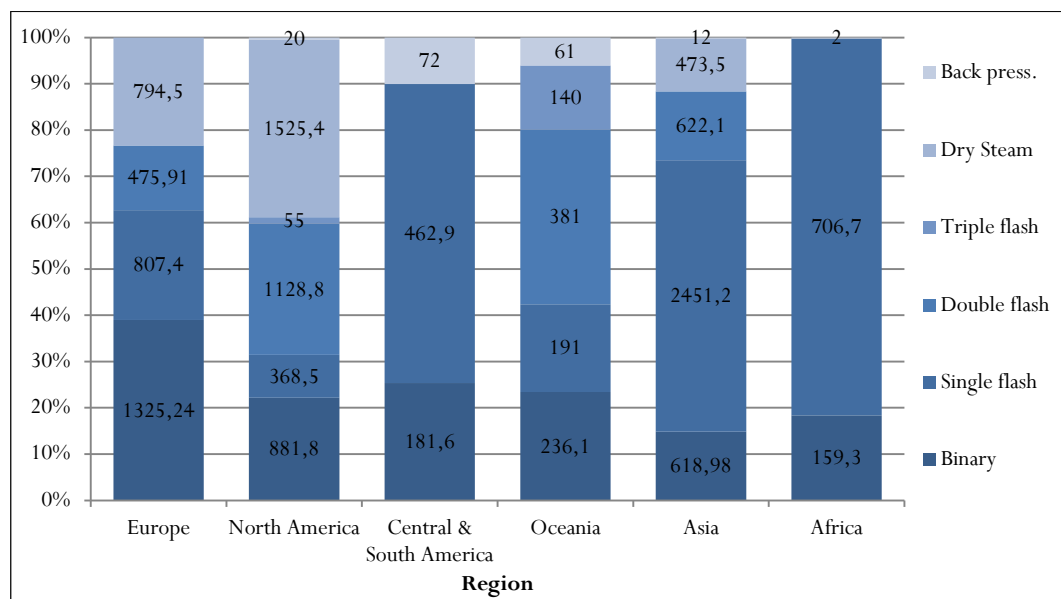


Figure 11. Installed capacity (MW) of geothermal power plants by region [50-62].

European installed capacity is rather gathered, as shown in Table 11 [50-62]. Turkey, Iceland and Italy markets represent 96% of the total and the technologies used by them fairly defined. In the case of Turkey, 76% of the installed capacity is in form of binary plants, being the remaining dry steam plants. Almost 99% of electricity generated by GE in Iceland is done by flash type technologies and in Italy a share of 87% corresponds to dry steam plants. The rest of Europe employs binary systems, except for a 5 MW_e plant in Iceland and the Flash systems of Guadeloupe (France).

³¹ Full data in Appendix B.

Table 11. Geothermal power installed capacity in Europe by country and technology (MW) [50-62].

Country	Binary	Single flash	Double flash	Dry Steam	Back pressure	Total
Austria	1.4	-	-	-	-	1.4
Belgium	4.5	-	-	-	-	4.5
Croatia	17.5	-	-	-	-	17.5
France	1.7	11	4.7	-	-	17.7
Germany	48.95	-	-	-	-	48.95
Hungary	3.35	-	-	-	-	3.35
Iceland	3.5	687.4	60	-	5	755.9
Italy	1	120	-	794.5	-	915.5
Portugal	33	-	-	-	-	33
Romania	0.05	-	-	-	-	0.05
Turkey	1 296.39	-	399.91	-	-	1 696.3
Total	1 411.34	818.4	464.61	794.5	5	3 494.15

3.3.2 Direct use

Despite the many applications of direct use GE, about 80% of the total use corresponds to space heating and bathing and swimming pools [35]. A promising utilization is as supply for district heating systems (DHS). In Europe there are more than 5 000 DHS [45], of which approximately 298 are supplied with geothermal heat. Approximate current capacities and 2025 perspectives are listed in Table 12 [45], [50], [63]. The installed capacity is larger than 59 657.8 MW_{th} and the yearly yield more than 159 566.8 GWh_{th}/yr. It was expected that by the year 2020, nearly all the countries in Europe would have GeoDH [64]. Nowadays, although DH is implemented in almost all European territories (all except Albania and Belarus [50]), those sourced with GE are not as widely available and the implantation level is highly variable. Largest production is by far that of Serbia, followed by Iceland (more than 16 times lower), Turkey and France. The rest of the countries listed have a production below 1 000 GWh_{th}/yr and only four above 300 GWh_{th}/yr. Predicted increase by the year 2025 is 11 209.9 GW_{th} in capacity, producing 61 260.7 GWh_{th}/yr more. However, more than 95% of the expected production growth is represented by France, Turkey and Serbia.

Some countries account remarkable contributions of geothermal energy for other uses³². For example, France provides 130 774 GWh_{th}/yr of heating/cooling through 15 large systems for other uses than DH.

³² See Appendix C.

Serbia has an installed capacity of 137 836 MW_{th} intended to supply 15 740 GWh_{th}/yr for agriculture, forestry, building heating, balneology and other similar uses. In the case of Turkey 4 244 MW_{th} are installed to supply heat to the agriculture and industry sectors and 7 300 MW_{th} for balneology and other minor applications.

But, the most widely use of direct-use of geothermal heat is by means of GSHPs. More than 1 865 217 units are installed with a capacity of 38 978.72 MW_{th}. The main contributor to this numbers is Sweden, which account with almost 593 990 GSHPs. But the bigger producer is Serbia, with a yearly yield of 34 366 GWh_{th} thanks to this technology.

Table 12. Geothermal DHS in Europe in 2018 (including projects under construction) and 2025 predictions [45], [51], [62].

Country	No.	2018		2025	
		Capacity [MW _{th}]	Production [GWh _{th} /yr]	Capacity [MW _{th}]	Production [GWh _{th} /yr]
Austria	9	75.7	224.7	150	500
Belgium	4	26	14.5	7	11
Bosnia-Herzegovina	23	-	-	-	-
Croatia	3	42.3	44.7	61.3	77.7
Czech Republic	1	6.6	21	-	-
Denmark	3	33	-	500	-
Finland	-	40	-	80	-
France	59	616.2	1 651.6	1 658.2	-
Germany	25	384.5	893.3	450	-
Greece	-	-	-	41.2	59.4
Hungary	23	223.4	635.7	300	850
Iceland	28	2 367	9 327.5	-	-
Italy	16	161.7	237	188	-
Lithuania	1	18	34.1	18	34.1
Macedonia	2	42.6	106	-	128
The Netherlands	-	-	-	240	1 200
Norway	3	-	-	-	-
Poland	6	84.6	250.4	140	430 – 500
Portugal	2	2.1	15	10	70
Romania	12	160	305.2	-	-
Serbia	10	47 673	153 806	55 100	218 840
Slovakia	4	21.9	41.0	-	-
Slovenia	17	46.8	124.4	-	-
Spain	8	2.9	2.4	-	-
Switzerland	12	11.9	35.7	105	420
Turkey	18	1 453	4 600	2 200	6 965
UK	1	3	14.8	12	90
Total	292	53 497.1	172 385	61 260.7	229 245.2

3.4 Barriers & challenges

Identified barriers for the future development of the geothermal energy are environmental concerns, social perception, technological constraints, financing risks and administrative procedures [2], [9]. Nevertheless, IRENA recognize “*securing funding for surfaces exploration and drilling operations*” [9] as the main challenge. Future potential will depend on overcoming such technical barriers as the demonstration of innovative, non-mechanical drilling techniques.

3.4.1 Environmental and social concerns

GE presents environmental advantages when compared to other energy sources, but also hazards exist. Bigger magnitude events are related to geological risks and gaseous or solid substances emissions, but those concerning groundwater use and contamination are of no less importance [22]. Moreover, countries having specific legislation take into consideration “protection of groundwater as a resource for drinking water” and, a majority of them, release of “hazardous materials” [65].

Despite they are considered as “not an obstacle” and almost entirely manageable [9], [34], they constitute the main inducer of social concerns.

To afford this challenge, environmental mitigating measures must be taken and monitoring systems³³ placed to control, prevent and manage ongoing impacts and possible side effects. On the other hand, social issues could be handled through discussions and negotiations [9].

3.4.2 Financing

The substantial capital requirements, especially those linked to exploration drilling costs are the main barrier for the development of geothermal projects [9]. Figure 12 gives the cost-risk profile of a geothermal project development in the different phases [34]. According to it, it is not until after the drilling phase that the risk drops below the moderate level. By then, more than half of the total cost would have been spent [34].

³³ Balmatt power plant (Belgium) offers the opportunity to review the seismometer registers through the website <https://vito.be/en/vito-seismometer-network-investigates-earthquakes> [54].

If only “high risk” phases are considered, the total spends when overcoming the drilling test could range between 10 and 15%. If the construction of a 50 MW plant is considered at an average cost of € 3.7 million/MW, this would represent € 27.4 million.

This spent has to be done taking into account that the current success rate in drilling for geothermal projects is about 50 % in green fields and 75 % in operated fields [34].

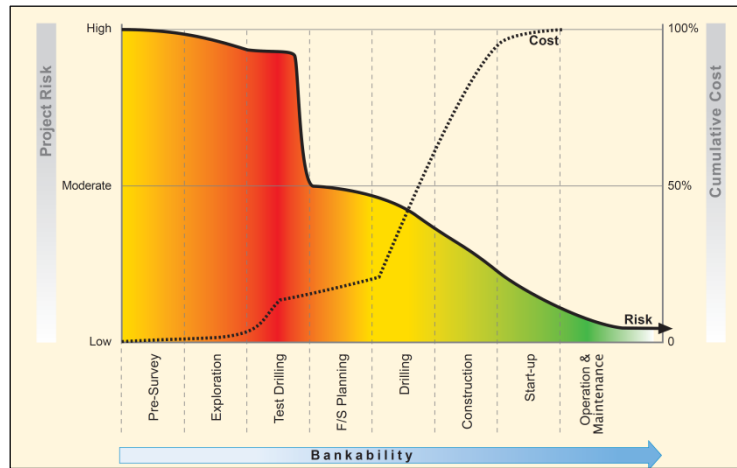


Figure 12. Project cost and risk profile at various stages of development [34].

Securing funding for surface exploration and drilling operations is highlighted as the most difficult point to overcome [9]. The GEORISK project [66], already working in countries such as Switzerland, France or Germany, aims to provide risk insurance for deep geothermal projects.

3.4.3 Drilling operations

Wellbore construction is an important part of a geothermal project. Coping with the harsh environment of the reservoirs without degrading the fluid is a challenge [67]. Even more so if the working depth increases to several kilometres. Related phases represent the second greater cost in the projects [9], [34], are rated as high-moderate risk [34] and the probability of success is 50 to 75% [34]. This is especially relevant in the case of EGS, whose deployment is crucial for the development of deep geothermal energy in Europe. In these systems, the drilling depth would reach up to 10 km, with consequent temperature and pressure conditions.

Several issues connected to wells can cause project failure. The transposition of knowledge and technology from the widespread oil and gas industry could be very valuable for deep geothermal systems, albeit it is unclear to what extent it could help to cut costs at greatest depths [22].

Components commonly used in hydrocarbon drilling, such as expandable tubular casing, under-reamers or drilling-with-casing methods, can be utilized in geothermal drilling as well [67], [68]. Albeit some differences exist, related to the fluid and the environment, between well drilling in both applications [67], [69]. Circulation loss, a manageable aspect in oil and gas wellbores, is not as easily afforded in geothermal, accounting for 10-20% of the drilling cost [69]. That is the consequence of the high temperatures and corrosive substances typically found in geothermal sites [69]. These are also responsible for other related problems like well cementing or casing failure. In both cases, materials used are affected in their performance due to these specific conditions [69]. Materials proven suitable for these circumstances are often uneconomical or lead to a decline in other important properties, such as strength [69]. Further research is needed to meet the requirements while achieving the economic objectives of the project.

Drilling is a priority in the cost optimization of the geothermal projects that can be addressed by improving drilling methods, employing new equipment and applying new construction solutions [69]. Wellbore construction means 45% of the work time of the project, being the drilling the main contributor, accounting for a 26% of this share [69]. The development of new drilling techniques promises to reduce the drilling costs of geothermal projects, making them more attractive, as for example spallation, laser and chemical drilling [68], [70]. Therefore, enhancement of drilling techniques is imperative for the operation of the geothermal sector [67].

3.4.4 Administrative

IRENA [9] indicates that administrative procedures require “*carefully attention by projects developers*”. At European level, no specific normative frame for geothermal exists, being it included in general “Renewable Energies” frames, resulting different and non-uniformed regulations for each country [9].

The review of Tsagarakis et al. [65] about shallow geothermal legislation in different EU countries, shows that despite of the sharp rise in the installations of GSHPs [5] it prevails a lack of regulation assisting the implementation SGE [65]. The paper concludes that among the 14 examined countries legal frame widely varies in extent and content, not even existing in some cases (Cyprus). This includes the lack of standardized definition or depth establishment of Shallow Geothermal Systems [65].

The lack of definition and specifications for geothermal energy may result in misunderstandings of requirements, prolonging and complicating procedures, and thus needs to be addressed by governments [9], [65].

3.4.5 Investment in R&D

Agreement exists about the feasibility of geothermal energy and the opportunities of enhancement of this industry, if determined research is carried with the required investment [21].

Between 2015 and 2019, Europe invested € 1.824 billion in research and development (R&D) in geothermal energy i.e. 8.7% of the total around the globe (53 countries for a total of € 21.078 billion). By contrast, Asia was the main supporter, accounting for 74.2% of the total. 64% was allocated to electric power. R&D included a 32.4% for field development and 24.3% for surface exploration [5].

Historical EU-28 investment (1974-2007) in research, development and demonstration (RD&D) in energy supply side technologies (approximately € 87 billion) has been directed to nuclear energy (fission and fusion), in particular, 78.5%. The corresponding expenditure in geothermal energy was less than 0.8% [70]. This investment is shown in Fig. 13 [71]. Among the renewable sources, greater attention has been received by solar, biomass and wind energies, although their massive implementation carries negative implications as well [21].

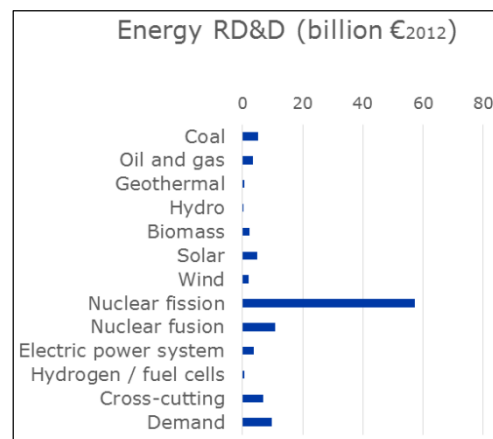


Figure 13. Energy RD&D (billion €₂₀₁₂) [71].

Despite the limited investment, a number of projects have been carried³⁴. The most relevant carried in the EU on EGS has been financed with € 90 million within the Horizon2020 Framework Programme between 2014 and 2018 [38]. For an equivalent period (2007 – 2013) the United States investment in this type of technologies was more than the double, € 208 million [37].

This leads to ask whether advance and improved geothermal technology would be currently ready if the same efforts dedicated to other sources would have been focus on it.

3.5 Scenarios & accomplishments

The theoretical and technical potential of geothermal energy is large, but its exploitation is conditioned to what can be considered as economically, environmentally and socially acceptable [2].

Predictions suggested a World's installed capacity of 16.8 to 18.4 GW_e before 2025 [9], [72], [73]. Nowadays, installed capacity rounds 14.2 GW_e, somewhat below the expectations. However, IRENA's [9] forecast by 2025³⁵ would be already achieved by all countries in Europe, except Italy, and some other not listed also account with geothermal power plants.

Nevertheless, current capacity i.e. 3.5 GW_e, would be well below economic potentials (reviewed in section 3.1.5 and summarized in Table 14 [16], [38], [43]) estimated by van Wees et al. [16] and Limberger et al. [43]³⁶, which gave a value of 19 GW_e. Even targets set in the National Renewable Energy Action Plans (NREAP) for EU member states for 2020 have not been accomplished. A total of 1.6 GW_e [16], producing 10 892 GWh [16], were expected, in contrast with the current capacity of 1.03 GW_e, which generated 6 701 GWh_e in 2020 [1]. Additionally, 6 605 TJ of deep thermal energy and $5.08 \cdot 10^5$ TJ of heat utilized by GSHP were projected. But the total thermal heat supplied in the EU-28 in 2019 was 202 632 TJ³⁷ [5].

³⁴ The web site <https://www.geothermalresearch.eu/> aims to visualize them.

³⁵ See Table B - 13.

³⁶ Economic potential by county suggested by both authors can be found in Table E - 1.

³⁷ Detailed consumption by country worldwide can be found in Table B - 14.

Table 13. Projected geothermal capacity [9].

Country	2025	>2025
	[MW]	[MW]
Croatia	16.5	36.5
Germany	13.2	66.1
Iceland	752.4	1 322.4
Italy	946.4	1 142.4
Portugal	27.8	53.8
Russia	95.2	150.2
Turkey	721.6	997.6
Subtotal	2 573.1	3 769
Australia	0.8	462.5
Chile	98	298
China	28.43	98.4
Costa Rica	368.5	368.5
El Salvador	204.2	304.4
Ethiopia	178.5	278.5
Guatemala	54.2	134.2
Indonesia	3 410.7	4 270.2
Japan	612	935.7
Kenya	932.16	1 247.2
Mexico	957.9	1 252.9
New Zealand	11 288	1 483.8
Nicaragua	190.2	412.2
Papua New Guinea	56	166
Philippines	2 104.4	2 834.4
USA	3 874.3	5 425.3
Total	26 931.39	23 741.2

The future development of GE in Europe is predicted by several studies in the basis of various scenarios. According to Dalla Longa et al. [38] for 2050, the European geothermal energy investment market (supply plus demand side) will be of about € 151 – 199/yr, “with the largest share of geothermal investments directed towards residences (about 70%) and commercial buildings (around 25%)” [38].

Table 14. Review of geothermal economic potential in Europe [16], [38],[43].

Study	2020	2030	2050
van Wees et al. [16]	21.2 TWh _e *	34 TWh _e *	2 570 TWh _e *
	144 TWh _e	171 TWh _e	4 000 TWh _e
Limberger et al. [43]	19 GW _e	22 GW _e	522 GW _e
Dalla Longa et al. [38]	25 TWh _e /yr	40-80 TWh _e /yr	100–210 TWh _e /yr
	20 TWh _{th} /yr	280-380 TWh _{th} /yr	880–1 050 TWh _{th} /yr

* Values for EU-28

However, geothermal power contribution would be significantly low (4 – 7 %), in comparison to other sources, depending on the final accomplishment of projections. Solar photovoltaics (PV) will be the major contributor (15 – 20 %), while wind energy share is widely variable predicted (6 – 34 %) [38]. In all scenarios, traditional geothermal systems (binary & flash) capacity rises, but do not vary significantly between them. The total growth will then entirely subject to the EGS deployment, that is greatly conditioned by the climate policy more than the technology costs [38]. For direct heat, same pattern is followed, but in this case, the conditioning factor would be its application in residential and commercial buildings, replacing natural gas [38].

However, this does not match with the scenarios reviewed³⁸ by Shortall et al. [4], where impact of technology cost and development is assessed. Results are shown in Table 15 [4]. The most optimistic scenario, “ProRES SET-Plan targets”, where $5 \cdot 10^6$ TJ of heat and $6 \cdot 10^5$ TJ of electricity are generated, is the only one where technology cost reduction is considered, namely € 800/kW versus € 9 000/kW in all the others.

Table 15. Scenarios and sensitivities of interest with regard to geothermal energy deployment [4].

Scenario	Heat 2050	Electricity 2050		Thermal use in DH 2050	
	[PJ]	[GW]	[PJ]	[GW]	[PJ]
Baseline	225	1.4	42	0	0
ProRES SET-Plan targets	5 046	75.9	602	8	51
ProRES (Res 1)	2 357	9.8	279	0	0
ProRES Nearly Zero Carbon	1 816	4.2	61	180	1 134
Diversified without capturing of CO ₂ in power sector	1 912	8.1	239	3.9	25
Diversified (Div 1)	333	1.8	51	0	0

What seems clear is that the final potential will depend on EGS, that could be reduced up to 90% if these system are not well developed [4], [38].

The most optimistic of these scenarios is 6 to 9 times lower than the economic potential for 2050 [38], [58], and even so a growth of 2 127% in relation to current capacity would be needed.

³⁸ The model presented comprises the EU-28 territories plus Switzerland, Iceland and Norway and propose 13 scenarios. Five of them are considered of interest to geothermal. Details about the scenarios are given in [74].

4 Discussion

New energy targets require alternative energy sources, including geothermal energy. Its greatest advantage is that it can replace fossil fuels and nuclear energy by providing base energy, if they are wanted to be replaced, something hardly achievable by other clean sources of more generalized use. Despite a potential risk of pollution of air, soil and water with several gases and metal salts, emissions are lower than with other sources, which can contribute to accomplish climate targets. Another risk comes from geological hazards, such as subsidence and landslides, which can ultimately cause major damage. Induced seismicity also occurs in geothermal sites, constituting an important social concern. However, the risk is significantly lower than in other activities, which in any case have been carried out, and control measures can be put on place. At the same time, it can contribute to the independency of territories, which would have an impact both at state and regional levels, being especially beneficial for remote regions of complex connection. In addition, energy produced by geothermal means is cheap and reliable, being cost competitive.

Nevertheless, upfront costs together with the high risk that the development of a geothermal project implies constitute the main barrier for its utilization. That is especially relevant regarding drilling phases, a critical activity, characterized by high cost, technical limitations and uncertainties, with a success rate of 75% and only 50% in new fields. But it has to be said, that successful projects are considered economic beneficial.

The lack of specific and consistent regulation is also unhelpful to incentivize geothermal developments, since a clear frame of action and guidelines are not given, thus complicating the understanding of the requirements and the administrative procedures needed to be followed. This fact, together with the negligible investment in R&D in compare to other energies, can be a measure of the interest given to geothermal energy. Moreover, this is linked to the early stage of development of EGS, that of course requires involvement and investment, and is the key to deep geothermal energy utilization in Europe.

The importance of develop such systems relies in the fact that even if the theoretical potential could supply the full energy demand of the continent, with current technology utilization only a small fraction geographically restricted is extractable. EGS promise to strongly widespread suitable locations, helping geothermal energy to have a weight in the energy mix.

Utilization perspectives by 2050 are optimistic. Technological developments would be large, costs low and facilities numerous and diffused. Finally, geothermal energy would appear in the statistics. But the truth is that those perspectives seem difficult to reach. Despite the good intentions, the exploration permissions given, experimental drilling requests, development projects, etc. planned capacity seems overly ambitious, considering the pace of growth and the state of the technology, and that barriers to development slowly coming down.

5 Conclusions

5.1 Study results

Geothermal energy, in spite of present some risks (as any other energy), offers good opportunities for the energy mix of the future. That is to say, to supply baseload energy, at a low price, from a locally available and renewable source. At the same time, it can help to reduce global warming and environmental impact thanks to its low emissions.

However, significant challenges remain; some of them manageable, others more difficult to overcome. Much can be done, but it takes determination. What seems clear is that future potential will depend on overcoming technical barriers and reducing financial risk, to make geothermal energy not only theoretically competitive but also in the real World. And that needs involvement and funding, thus a change in current direction. It remains to be seen whether the next few decades will be seen a turnaround that will make geothermal energy the energy of the future.

5.2 Outlook

The study has revealed a number of drawbacks for the development of geothermal energy, as those included in the section “Barriers & challenges”. Its evolution in the coming years is to be reviewed. The same applies for the projections and targets related to geothermal energy deployment and their achievement in the future. That is to say, that this study represents a specific time. The development of periodical updates would make it possible not only to reflect more accurate contents in the next years, but also to provide equivalent information that would make it easier to monitor such evolution.

Various aspects of geothermal energy have been reviewed and are listed under each heading. Any one of them can be a subject of study in itself. In any case, some of them are of particular importance for several reasons, such as their relevance for sustainability, their role for development or the need for more data. This includes the environmental impact (some authors report a lack of emission measurements), the different fields of drilling operations, the economics of using geothermal for heat or the use of GE as base and flexible load.

5.3 Perspectives

The importance of the study resides in the opportunity offered by geothermal energy to advance towards a sustainable energy system. Although the weight it will have in future energy mix is uncertain, the theoretical approach indicates that it would fulfill the three dimensions of sustainable development: it would help reduce the environmental impact of energy consumption, with a local and reliable source, which could improve the well-being of populations, all in a cost-effective way.

While the current technology development is far from what is needed for the widespread harnessing of geothermal energy on a continental scale, the opportunities are clear, hence the importance of continuing to work on the development of geothermal energy to make it a reality in the energy mix of the future.

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Appendix A

Table A - 1. Research resources.

Library of University of Gävle	https://www.hig.se/Ext/En/University-of-Gavle/Library.html https://www.hig.se/Ext/En/University-of-Gavle/Library/Search/Databases-and-articles/Databases-A-to-Z.html
IEEE Xplore	https://ieeexplore.ieee.org/Xplore/home.jsp
Google Scholar	https://scholar.google.com/
Science Direct	https://www.sciencedirect.com/
International Energy Agency	https://www.iea.org/
International Renewable Energy Agency	https://www.irena.org/
International Geothermal Association	https://www.lovegeothermal.org/
Think Geoenergy	https://www.thinkgeoenergy.com/
European Commission	https://ec.europa.eu/info/index_en https://ec.europa.eu/info/publications_en https://cordis.europa.eu/en https://ec.europa.eu/eurostat
GeoDH	http://geodh.eu/

Appendix B

Table B - 1. TES evolution in the World and in Europe between 1990 and 2019 [1].

Year	World		Europe	
	[TJ]	Δ[%]	[TJ]	Δ[%]
1990	365 828 914	0.63	87 697 592	-0.23
1991	368 125 438	0.07	87 498 068	-3.84
1992	368 387 971	1.03	84 137 282	-1.49
1993	372 172 944	0.77	82 885 033	-2.29
1994	375 048 911	2.53	80 985 061	2.61
1995	384 539 960	2.53	83 101 955	2.65
1996	394 271 022	1.03	85 301 593	-0.78
1997	398 322 908	0.52	84 636 259	0.26
1998	400 390 672	2.22	84 855 720	-1.00
1999	409 280 333	2.32	84 007 421	1.03
2000	418 792 406	0.86	84 876 641	1.88
2001	422 414 723	2.18	86 468 857	0.18
2002	431 635 119	3.56	86 620 515	2.67
2003	447 013 540	4.47	88 930 099	1.13
2004	467 010 233	2.83	89 936 805	0.37
2005	480 236 567	2.91	90 273 982	0.85
2006	494 196 808	2.70	91 041 092	-1.04
2007	507 559 929	1.18	90 096 190	-0.15
2008	513 551 386	-1.03	89 962 082	-5.95
2009	508 251 214	5.55	84 607 375	3.55
2010	536 470 815	1.56	87 614 759	-1.91
2011	544 849 309	1.22	85 943 987	-0.47
2012	551 492 767	1.46	85 537 636	-1.51
2013	559 537 415	1.32	84 242 970	-3.86
2014	566 949 587	0.24	80 993 483	0.80
2015	568 322 391	0.79	81 641 841	0.71
2016	572 826 975	2.13	82 219 827	1.63
2017	585 039 123	2.50	83 556 613	-0.47
2018	599 682 535	1.14	83 162 175	-1.93
2019	606 489 570	-	81 559 568	-

Table B - 2. TES by source in the World, Europe and the EU-28, in 2019 [1].

Source	World		Europe		EU - 28	
	[TJ]	[%]	[TJ]	[%]	[TJ]	[%]
Oil	187 364 800	30.9	25 901 281	31.8	21 734 851	33.1
Coal	162 375 732	26.8	11 293 304	13.8	7 559 860	11.5
Natural gas	140 784 380	23.2	20 932 232	25.7	16 848 761	25.6
Nuclear	30 461 171	5.0	10 166 636	12.5	8 965 539	13.6
Hydro	15 194 639	2.5	2 241 261	2.7	1 172 942	1.8
Biofuels and waste	56 813 210	9.4	7 645 042	9.4	6 914 603	10.5
Wind, solar, etc.	13 417 236	2.2	3 379 812	4.1	2 548 331	3.9
Total	606 411 168		81 559 568		65 744 887	
Share of the World's total			13.5%		10.8%	

Table B - 3. TES by source in Europe between 1990 and 2019 [1].

Source	1990	1991	1992	1993	1994	1995	1996	1997
Coal	24 155 553	22 810 283	21 503 668	20 056 892	18 986 299	18 834 809	18 343 180	17 892 683
Natural gas	17 346 559	17 768 578	17 312 353	17 521 310	17 065 351	18 063 280	19 802 586	19 316 328
Nuclear	9 768 029	10 017 103	10 090 140	10 485 520	10 389 117	10 654 667	11 248 940	11 377 645
Hydro	1 774 688	1 806 219	1 872 080	1 946 927	1 971 959	2 006 501	1 951 464	2 008 113
Wind, solar, etc.	233 978	230 277	242 743	259 639	261 022	269 667	291 425	314 646
Biofuels & waste	2 494 575	2 585 496	2 620 972	2 778 446	2 779 007	2 919 827	3 072 563	3 184 860
Oil	31 924 210	32 280 112	30 495 326	29 836 299	29 532 306	30 353 204	30 591 435	30 541 984
Total	87 697 592	87 498 068	84 137 282	82 885 033	80 985 061	83 101 955	85 301 593	84 636 259

(Continuation)

Source	1998	1999	2000	2001	2002	2003	2004	2005
Coal	17 366 494	16 308 900	16 947 498	16 838 671	16 863 777	17 488 668	17 231 433	16 793 044
Natural gas	19 533 190	20 309 040	20 751 535	21 322 080	21 336 997	22 323 863	22 912 129	23 587 524
Nuclear	11 283 732	11 363 958	11 445 537	11 809 988	11 956 607	12 058 570	12 252 268	12 114 495
Hydro	2 100 547	2 117 377	2 178 647	2 171 606	1 993 251	1 876 897	2 020 191	2 036 969
Wind, solar, etc.	352 044	387 063	446 546	463 137	513 138	578 261	638 467	696 431
Biofuels & waste	3 223 321	3 228 191	3 334 324	3 411 434	3 516 469	3 830 230	3 978 577	4 354 915
Oil	30 996 392	30 292 892	29 772 554	30 451 941	30 440 276	30 773 610	30 903 740	30 690 604
Total	84 855 720	84 007 421	84 876 641	86 468 857	86 620 515	88 930 099	89 936 805	90 273 982

(Continuation)

Source	2006	2007	2008	2009	2010	2011	2012
Coal	17 609 711	17 816 549	16 817 746	14 998 401	14 779 286	16 287 569	16 653 386
Natural gas	23 156 483	23 142 977	23 546 945	21 648 426	23 888 208	21 812 187	21 172 213
Nuclear	12 094 260	11 531 377	11 520 432	10 969 936	11 267 110	11 174 732	10 895 327
Hydro	2 002 772	2 004 732	2 108 355	2 098 066	2 306 006	2 022 944	2 229 164
Wind, solar, etc.	784 958	915 042	1 021 913	1 130 785	1 269 367	1 531 332	1 733 283
Biofuels & waste	4 678 752	5 056 061	5 441 163	5 695 983	6 243 335	6 109 010	6 585 660
Oil	30 714 156	29 629 452	29 505 528	28 065 778	27 861 447	27 006 213	26 268 603
Total	91 041 092	90 096 190	89 962 082	84 607 375	87 614 759	85 943 987	85 537 636

(Continuation)

Source	2013	2014	2015	2016	2017	2018	2019
Coal	16 109 148	15 067 417	14 705 949	13 935 910	13 499 933	13 208 539	11 293 304
Natural gas	20 882 375	18 916 784	19 194 880	20 176 417	21 033 586	20 829 355	20 932 232
Nuclear	10 768 059	10 832 688	10 564 594	10 281 688	10 214 326	10 231 489	10 166 636
Hydro	2 356 222	2 292 004	2 266 540	2 323 217	2 082 167	2 295 697	2 241 261
Wind, solar, etc.	1 962 402	2 136 958	2 438 786	2 525 476	2 854 525	3 038 261	3 379 812
Biofuels & waste	6 749 197	6 674 566	6 895 024	7 099 556	7 283 306	7 422 544	7 645 042
Oil	25 415 567	25 073 066	25 576 068	25 877 563	26 588 770	26 136 290	25 901 281
Total	84 242 970	80 993 483	81 641 841	82 219 827	83 556 613	83 162 175	81 559 568

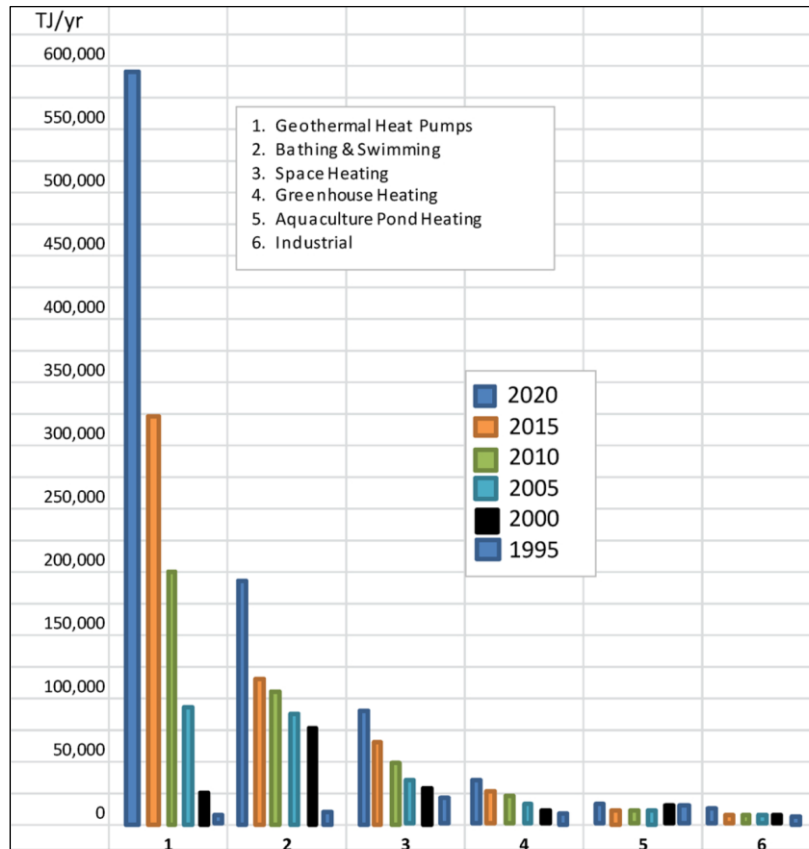


Figure B - 1. Comparison of worldwide direct-use of geothermal energy in TJ/yr from 1995, 2000, 2005, 2010, 2015 and 2020 [5].

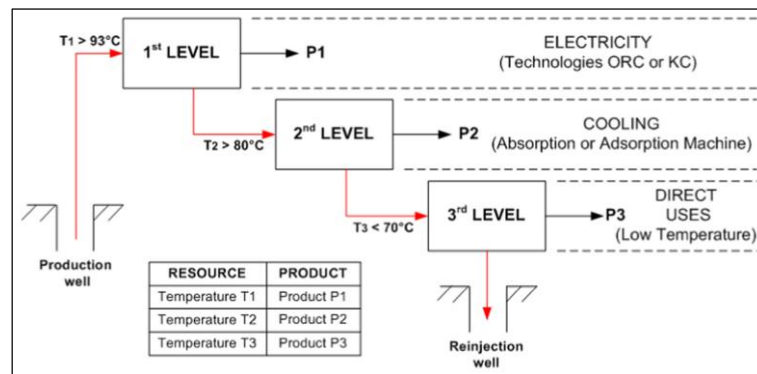


Figure B - 2. Conceptual diagram of the cascade utilization of geothermal energy [15].

Table B - 4. Summary of capacity factors for various categories of direct-use for the period 1990 – 2020 [5].

Utilization	Capacity factor					
	2020	2015	2010	2005	2000	1995
Geothermal heat pumps	0.245	0.206	0.192	0.180	0.140	0.250
Space heating	0.405	0.370	0.371	0.401	0.417	0.470
Greenhouse heating	0.462	0.467	0.478	0.467	0.455	0.460
Aquacultural pond heating	0.463	0.545	0.559	0.565	0.615	0.390
Agricultural drying	0.435	0.400	0.415	0.407	0.445	0.532
Industrial uses	0.610	0.540	0.699	0.712	0.684	0.590
Bathing and swimming	0.473	0.415	0.518	0.487	0.637	0.310
Cooling/snow melting	0.189	0.229	0.183	0.174	0.296	0.310
Other	0.584	0.578	0.721	0.385	0.702	0.300
Total	0.300	0.265	0.277	0.307	0.399	0.412

Table B - 5. Gas emissions in various power plants [28].

Emission	CO ₂ [kg/MWh]	SO ₂ [kg/MWh]	NO _x [kg/MWh]	PMs [kg/MWh]
Lignite	940–1 250	4.71	1.955	1.012
Coal fired	994	5.44	1.814	
Oil fired	758	$9.98 \cdot 10^{-2}$	1.343	$6.35 \cdot 10^{-2}$
Gas fired	550			
Biomass	40–100			
<i>Solar</i>				
Monocrystalline silicone	60–200			
PV Polycrystalline SOG-Si	99	$2.28 \cdot 10^{-4}$	$3.40 \cdot 10^{-4}$	$1.19 \cdot 10^{-4}$
Nuclear	15–30			
Fission power generation	22.25			
<i>Wind</i>				
Onshore 1.5 MW	10.2	$3.95 \cdot 10^{-5}$	$3.11 \cdot 10^{-5}$	$4.22 \cdot 10^{-5}$
Offshore 2.5 MW	8.9	$3.54 \cdot 10^{-5}$	$2.09 \cdot 10^{-5}$	$1.09 \cdot 10^{-5}$
<i>Hydroelectric</i>				
Hydropower 3.1 MW _{el}	10	$1.70 \cdot 10^{-5}$	$3.6 \cdot 10^{-5}$	$2.60 \cdot 10^{-5}$
<i>Geothermal</i>				
EGS	16.9–49.8			
Binary	42–62	$(3.5–5.1) \cdot 10^{-4}$		
Single-ORC	80.49	$2.50 \cdot 10^{-4}$		
Flash-ORC	13	$4.00 \cdot 10^{-5}$		
Single flash	12	$6 \cdot 10^{-5}$		
Double flash	3.88	$3.04 \cdot 10^{-5}$		
Hydrothermal Geysers-dry (steam field)	40.3	$9.8 \cdot 10^{-5}$	$5.8 \cdot 10^{-4}$	Negligible
Hydrothermal flash-steam (liquid dominated)	27.2	$1.588 \cdot 10^{-1}$	0	0
Hydrothermal closed-loop binary	0	0	0	Negligible

Table B - 6. Geothermal economic potential in Europe [42].

Country	2020	2030	2050
	LCOE < 300	LCOE < 200	LCOE < 200
Austria	0.12	0.22	11
Belarus	-	-	2
Belgium	-	-	4
Bosnia-Herz.	0.09	0.11	5
Bulgaria	-	-	13
Croatia	0.98	0.87	7
Czech Republic	-	-	7
Denmark	-	-	5
Finland	-	-	2
France	0.34	0.96	99
Germany	1.22	1.99	53
Greece	0.39	0.37	15
Hungary	4.74	4.04	24
Iceland	16.30	14.30	43
Ireland	-	-	5
Italy	2.77	2.54	36
Latvia	-	-	1
Lithuania	-	0.05	4
Macedonia	-	-	2
Moldova	-	-	2
Netherlands	0.36	0.52	7
Norway	-	-	8
Poland	0.03	0.13	29
Portugal	-	-	10
Romania	0.15	0.23	22
Serbia	0.64	0.66	14
Slovakia	0.42	0.48	8
Slovenia	0.04	-	2
Spain	0.28	0.39	59
Sweden	-	-	14
Switzerland	-	0.16	6
Turkey	15.80	14.50	135
Ukraine	0.13	0.24	27
United Kingdom	0.03	0.05	15
Total	44.83	42.81	696

Table B - 7. Comparison of different power plants based on landuse [28].

Power plant	Land use [m ² /MW]	Comparison
Geothermal flash plant	1 260	Baseline
Geothermal binary plant	1 415	1.12
Geothermal flash plant (incl. wells)	7 460	5.92
Wind farm	16 000	12.69
Nuclear plant	10 000	7.93
Solar thermal plant	28 000	22.22
Coal plant (incl. strip mining)	40 000	31.74
Solar PV plant	66 000	52.39

Table B - 8. Indicative costs for geothermal development of two 100 MWe plant [9].

Phase / Activity	Share [%]
Power plant	42
Infrastructure	7
Exploration wells	4
Test wells	1
Steamfield development	14
Production wells	15
Injection wells	4
Owner's cost	1
Project management and engineering supervision	3
Contingency	9
Total cost [€/kW]	3 626

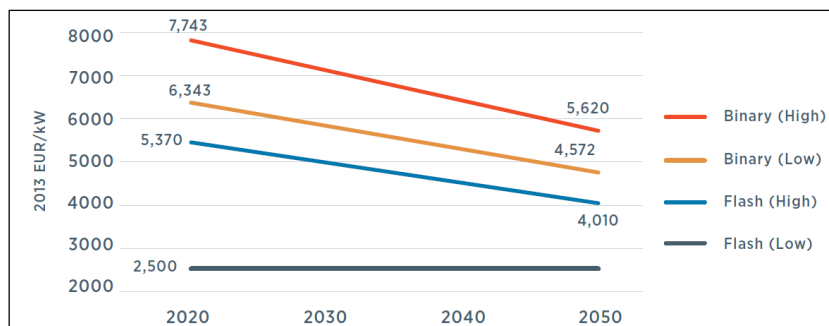


Figure B - 3. Forecast of CAPEX for geothermal power plant in the EU [24].

Table B - 9. Geothermal energy capital costs in industry and agriculture [37].

Technology	Sector	CAPEX [M€/PJ/yr]			
		2010		2050	
		Range	Avg	Range	Avg
Direct use conventional	Agriculture	90	90	78	78
Direct use EGS	Agriculture	136	136	116	116
Steam and process heat conventional	Chemicals	39-117	79	39-117	79
Steam and process heat EGS	Chemicals	58-177	117	58-177	117
Steam and process heat conventional	Iron and steel	48-137	93	48-137	93
Steam and process heat EGS	Iron and steel	73-206	140	73-206	140
Steam and process heat conventional	Pulp and paper	39-112	76	39-112	76
Steam and process heat EGS	Pulp and paper	58-168	113	58-168	113
Steam and process heat conventional	Non-ferrous metals	39-117	79	39-117	79
Steam and process heat EGS	Non-ferrous metals	58-177	117	58-177	117
Steam and process heat conventional	Non-metals	39-142	91	39-142	91
Steam and process heat EGS	Non-metals	58-213	135	58-213	135
Steam and process heat conventional	Other industries	39-117	79	39-117	79
Steam and process heat EGS	Other industries	58-177	117	58-177	117

Table B - 10. Main features conditioning the sustainability of geothermal systems [38].

System	Renewability
GHP Horizontal	Constant atmospheric heat supply (longevity guaranteed).
Heating/cooling GHPs	Heat balance (winter-summer) given by the design.
Groundwater coupled GHPs	Heat assured by both the geothermal flow and the atmosphere. Fluid secured by the hydrologic cycle.
BHE-coupled GHP	Depending on hydrogeological characteristics and subject to the design.
Hydrothermal aquifer	Depending on the production rate, the distance between the boreholes, as well as on the physical and geometric properties of the reservoir.
High-enthalpy two-phase reservoir	Reinjection, required to avoid depletion, can cause temperature decrease in the reservoir volume. Production rates dictated by economic limit the productive lifetime.
HDR/EGS	Thermal recovery of the rock mass after production stops. Moderate production rates can secure longevity with similar total energy yields. Depending on utilization technology and local geological conditions.

Table B - 11. Potential environmental effects of geothermal systems [30].

System	GW	AC	HT	AD
	[gCO _{2eq} /kWh]	[gSO _{2eq} /kWh]	[g1.4DB _{eq} /kWh]	[gSB _{eq} /kWh]
Dry steam	312.51	3.51	8.04	0.41
Flash plants	158.52	4.37	2.01	0.05
EGS-binary	31.57	0.16	16.47	$8.60 \cdot 10^{-10}$
Deep geothermal	46.15	0.19	11.90	0.02
CHP	69.73	1.19	4.90	$1.69 \cdot 10^{-4}$

Table B - 12. Emission from different energy sources [28].

Source	CO ₂	SO ₂	NO _x	PMs
	[kg/MWh]	[kg/MWh]	[kg/MWh]	[kg/MWh]
Lignite	940 – 1 250	4.71	1.955	1.012
Coal fired	994	5.44	1.814	
Oil fired	758	$9.98 \cdot 10^{-2}$	1.343	$6.35 \cdot 10^{-2}$
Gas fired	550			
Biomass	40 – 100			
<i>Solar</i>				
Monocrystalline silicone	60 – 200			
PV Polycrystalline SOG-Si	99	$2.28 \cdot 10^{-4}$	$3.40 \cdot 10^{-4}$	$1.19 \cdot 10^{-4}$
Nuclear	15 – 30			
Fission power generation	22.25			
<i>Wind</i>				
Onshore 1.5 MW	10.2	$3.95 \cdot 10^{-5}$	$3.11 \cdot 10^{-5}$	$4.22 \cdot 10^{-5}$
Offshore 2.5 MW	8.9	$3.54 \cdot 10^{-5}$	$2.09 \cdot 10^{-5}$	$1.09 \cdot 10^{-5}$
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Hydropower 3.1 MW _{el}	10	$1.7 \cdot 10^{-5}$	$3.6 \cdot 10^{-5}$	$2.60 \cdot 10^{-5}$
<i>Geothermal</i>				
EGS	16.9 – 49.8			
Binary	42 – 62	$(3.5-5.1) \cdot 10^{-4}$		
Single-ORC	80.49	$2.50 \cdot 10^{-4}$		
Flash-ORC	13	$4 \cdot 10^{-5}$		
Single flash	12	$6 \cdot 10^{-5}$		
Double flash	3.88	$3.04 \cdot 10^{-5}$		
Hydrothermal Geysers-dry (steam field)	40.3	$9.8 \cdot 10^{-5}$	$5.8 \cdot 10^{-4}$	Negligible
Hydrothermal flash-steam (liquid dominated)	27.2	$1.588 \cdot 10^{-1}$	0	0
Hydrothermal closed-loop binary	0	0	0	Negligible

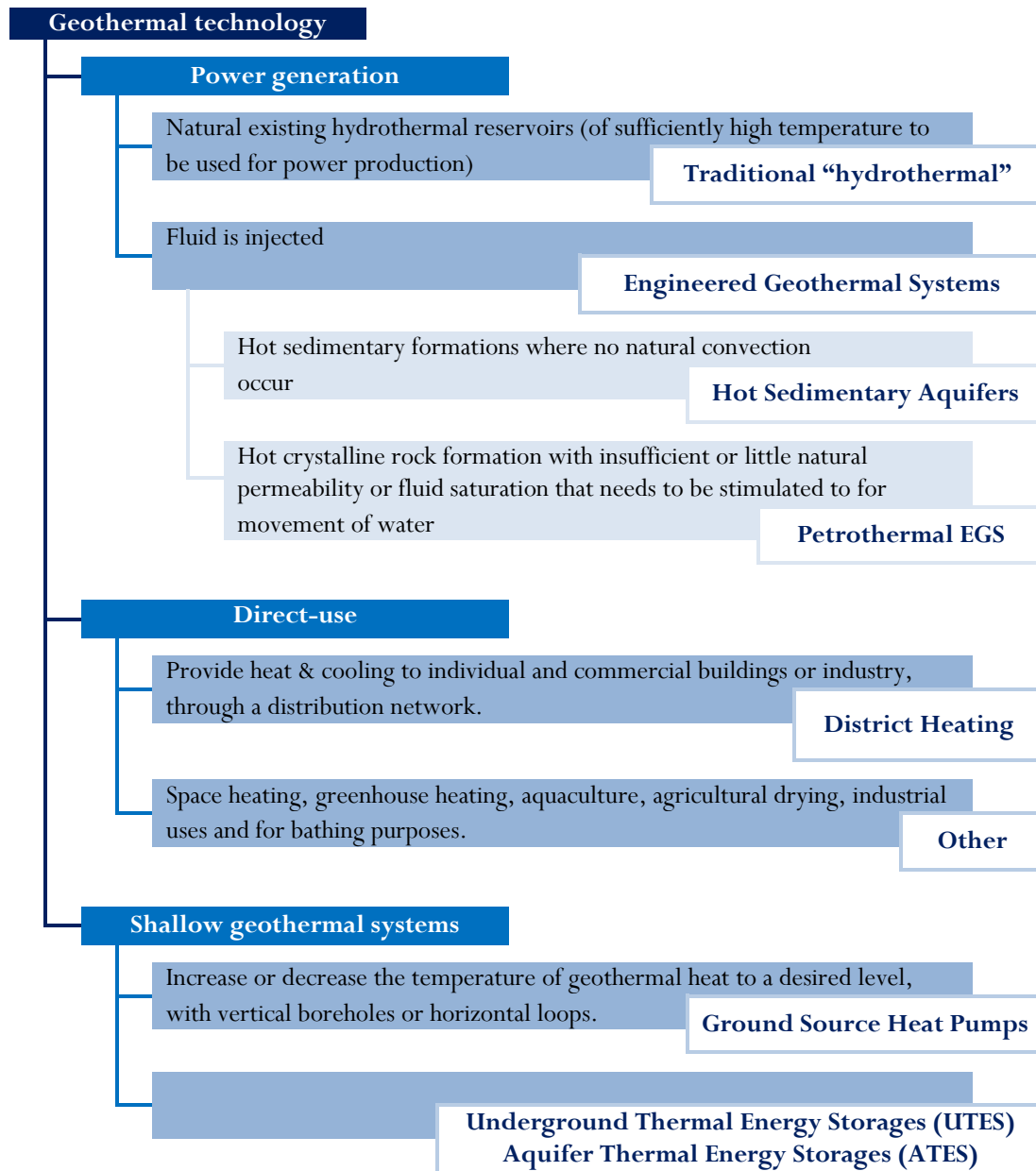


Figure B - 4. Geothermal technology description [4].

Table B - 13. Projected geothermal capacity [9].

Country	2025	>2025
	[MW]	[MW]
Croatia	16.5	36.5
Germany	13.2	66.1
Iceland	752.4	1 322.4
Italy	946.4	1 142.4
Portugal	27.8	53.8
Russia	95.2	150.2
Turkey	721.6	997.6
Subtotal	2 573.1	3 769
Australia	0.8	462.5
Chile	98	298
China	28.43	98.4
Costa Rica	368.5	368.5
El Salvador	204.2	304.4
Ethiopia	178.5	278.5
Guatemala	54.2	134.2
Indonesia	3 410.7	4 270.2
Japan	612	935.7
Kenya	932.16	1 247.2
Mexico	957.9	1 252.9
New Zealand	11 288	1 483.8
Nicaragua	190.2	412.2
Papua New Guinea	56	166
Philippines	2 104.4	2 834.4
USA	3 874.3	5 425.3
Total	26 931.39	23 741.2

Table B - 14. Direct-use of geothermal heat in the World, in 2019 [5].

Country	[MWt]	[TJ/yr]	[GWh/yr]	Load Factor
Austria	1 095.780	8 644.210	2 401.169	0.250
Belgium	305.720	1 467.500	407.639	0.152
Bulgaria	109.370	1 326.960	368.600	0.385
Croatia	79.300	390.600	108.500	0.156
Cyprus	10.300	65.000	18.056	0.200
Czech Republic	324.500	1 790.000	497.222	0.175
Denmark	743.600	4 002.000	1 111.667	0.171
Estonia	63.000	356.000	98.889	0.179
Finland	2 300.000	23 400.000	6 500.000	0.323
France	2 597.600	17 279.600	4 799.889	0.211
Germany	4 806.340	29 138.640	8 094.067	0.192
Greece	259.450	2 087.520	579.867	0.255
Hungary	1 023.700	10 701.620	2 972.672	0.331
Ireland	200.870	974.000	270.556	0.154
Italy	1 425.000	10 916.000	3 032.222	0.243
Latvia	1.630	31.810	8.836	0.619
Lithuania	125.500	1 044.000	290.000	0.264
Netherlands	1 719.150	8 344.000	2 317.778	0.154
Poland	756.000	4 175.980	1 159.994	0.175
Portugal	21.060	406.500	112.917	0.612
Romania	245.130	1 905.320	529.256	0.246
Slovakia	230.300	2 000.900	555.806	0.276
Slovenia	265.550	1 610.490	447.358	0.192
Spain	544.000	3 933.000	1 092.500	0.229
Sweden	6 680.000	62 400.000	17 333.333	0.296
United Kingdom	524.700	4 240.500	1 177.917	0.256
Total EU-28	26 457.550	202 632.150	56 286.710	0.258
Albania	16.225	107.590	29.886	0.210
Armenia*	1.500	22.500	6.250	0.476
Belarus	10.000	137.000	38.056	0.434
Bosnia & Herzegovina	36.030	306.710	85.197	0.270
Faroe Islands	3.660	20.000	5.556	0.173
Georgia*	69.200	2 186.220	607.283	1.000
Greenland	0.100	3.200	0.889	1.000
Iceland	2 373.000	33 598.000	9 332.778	0.449
Macedonia	47.430	623.610	173.225	0.417
Norway	1 150.180	12 601.200	3 500.333	0.347
Russia*	433.000	8 475.000	2 354.167	0.621
Serbia	115.302	1 726.141	479.484	0.475
Switzerland	2 196.800	13 292.000	3 692.222	0.192
Turkey*	3 488.350	54 584.000	15 162.222	0.496
Ukraine	1 606.960	5 085.950	1 412.764	0.100
Total Europe non EU-28	11 547.737	132 769.121	36 880.312	0.444
Total Europe	38 005.287	335 401.271	93 167.022	0.351

(Continuation)

Algeria	77.700	2 375.100	659.750	0.969
Argentina	204.780	1 209.070	335.853	0.187
Australia	94.400	853.000	236.944	0.287
Bolivia	1.000	20.000	5.556	0.634
Brazil	363.450	6 682.700	1 856.306	0.583
Burundi	0.350	7.000	1.944	0.634
Canada	1 831.280	14 512.000	4 031.111	0.251
Chile	22.610	278.910	77.475	0.391
China	40 610.000	443 492.000	123 192.222	0.346
Columbia	20.000	340.000	94.444	0.539
Costa Rica	1.750	35.000	9.722	0.634
Eastern Caribbean	0.103	2.775	0.771	0.854
Ecuador	5.201	103.461	28.739	0.631
Egypt	44.000	152.890	42.469	0.110
El Salvador	3.360	56.000	15.556	0.528
Ethiopia	2.200	41.600	11.556	0.600
Guatemala	2.310	56.460	15.683	0.775
Honduras	1.933	45.000	12.500	0.738
India	357.644	4 007.820	1 113.283	0.355
Indonesia	2.300	42.600	11.833	0.587
Iran	82.224	2 583.261	717.573	0.996
Israel	82.400	2 193.000	609.167	0.844
Japan	2 570.460	30 723.270	8 534.242	0.379
Jordan	153.300	1 540.000	427.778	0.319
Kenya	18.500	602.400	167.333	1.000
Madagascar	2.814	75.585	20.996	0.852
Malawi	0.550	11.000	3.056	0.634
Malaysia	5.000	100.000	27.778	0.634
Mexico	156.113	4 185.369	1 162.603	0.850
Mongolia	22.720	398.700	110.750	0.556
Morocco	5.000	50.000	13.889	0.317
Nepal	3.555	96.113	26.698	0.857
New Zealand	518.000	10 120.000	2 811.111	0.620
Nigeria	0.700	14.000	3.889	0.634
Papua New Guinea	0.100	1.000	0.278	0.317
Peru	3.000	61.000	16.944	0.645
Philippines	1.670	12.650	3.514	0.240
Saudi Arabia	45.000	172.890	48.025	0.122
South Africa	2.300	37.000	10.278	0.510
South Korea	1 489.760	3 482.650	967.403	0.074
Tajikistan	2.930	55.400	15.389	0.600
Thailand	128.510	1 181.200	328.111	0.291
Tunisia	43.800	364.000	101.111	0.264
United States of America	20 712.590	152 809.500	42 447.083	0.234
Venezuela	0.700	14.000	3.889	0.634
Viet Nam	18.210	188.520	52.367	0.328
Yemen	5.000	100.000	27.778	0.634
Total non-Europe	2 507.187	4 388.954	5 264.789	25.018
TOTAL WORLD	40 512.474	339 790.225	98 431.811	12.684

Appendix C

Table C - 1. World's geothermal power plants [48-60, 73].

Country	Plant	Technology	Capacity [MW]
Austria	Altheim	Binary	1.00
Austria	Bad Blumau	Binary	0.20
Austria	Simbach Braunau	Binary	0.20
<i>Austria Total</i>			<i>1.40</i>
Belgium	Balmatt	Binary	4.50
<i>Belgium Total</i>			<i>4.50</i>
Croatia	Velika Ciglena	Binary	17.50
<i>Croatia Total</i>			<i>17.50</i>
France	Soultz-sous-Forêts	Binary	1.70
France (Guadalupe)	La Bouillante	Double Flash	16.00
<i>France Total</i>			<i>17.70</i>
Germany	Bruchsal	Binary	0.55
Germany	Dürrnhaar	Binary	6.00
Germany	Garching an der Alz, Altötting	Binary	4.90
Germany	Grünwald	Binary	4.30
Germany	Holzkirchen	Binary	3.60
Germany	Insheim	Binary	4.80
Germany	Kirchstockach	Binary	6.00
Germany	Kirchweidach	Binary	1.00
Germany	Landau	Binary	3.00
Germany	Sauerlach	Binary	5.00
Germany	Taufkirchen	Binary	4.30
Germany	Traunreut	Binary	5.50
Germany	Unterhaching	Binary	0.00
<i>Germany Total</i>			<i>48.95</i>
Hungary	Tura	Binary	3.35
<i>Hungary Total</i>			<i>3.35</i>
Iceland	Bjarnarflag	Back Pressure	5.00
Iceland	Hellisheidi	Single Flash	213.00
Iceland	Hellisheidi Stage 5	Single Flash	90.00
Iceland	Húsavík	Binary	0.00
Iceland	Kópsvatn	Binary	1.20
Iceland	Krafla	Double Flash	60.00
Iceland	Nesjavellir	Single Flash	120.00
Iceland	Reykholt	Binary	0.30
Iceland	Reykjanes	Single Flash	100.00
Iceland	Svartsengi	Single Flash	74.40
Iceland	Theistarykir	Single Flash	90.00
<i>Iceland Total</i>			<i>753.90</i>
Italy	Bagnore 3	Single Flash	20.00
Italy	Bagnore 4	Single Flash	40.00
Italy	Bagnore binary (Bagnore 3)	Binary	1.00
Italy	Carboli 1	Dry Steam	20.00
Italy	Carboli 2	Dry Steam	20.00
Italy	Chiusdino 1	Dry Steam	20.00
Italy	Cornia 2	Dry Steam	20.00
Italy	Farinello	Dry Steam	60.00

Italy	La Prata	Dry Steam	20.00
Italy	Monteverdi 1	Dry Steam	20.00
Italy	Monteverdi 2	Dry Steam	20.00
Italy	Nuova Castelnuovo	Dry Steam	14.50
Italy	Nuova Gabbro	Dry Steam	20.00
Italy	Nuova Lago	Dry Steam	10.00
Italy	Nuova Lagoni Rossi	Dry Steam	20.00
Italy	Nuova Molinetto	Dry Steam	20.00
Italy	Nuova Monterotondo	Dry Steam	10.00
Italy	Nuova Radicondoli	Dry Steam	40.00
Italy	Nuova Radicondoli GR 2	Dry Steam	20.00
Italy	Nuova San Martino	Dry Steam	40.00
Italy	Nuova Sasso	Dry Steam	20.00
Italy	Nuova Serrazzano	Dry Steam	60.00
Italy	Pianacce	Dry Steam	20.00
Italy	Piancastagnaio 3	Single Flash	20.00
Italy	Piancastagnaio 4	Single Flash	20.00
Italy	Piancastagnaio 5	Single Flash	20.00
Italy	Rancia	Dry Steam	20.00
Italy	Rancia 2	Dry Steam	20.00
Italy	Sasso 2	Dry Steam	20.00
Italy	Selva	Dry Steam	20.00
Italy	Sesta	Dry Steam	20.00
Italy	Travale 3	Dry Steam	20.00
Italy	Travale 4	Dry Steam	40.00
Italy	Valle Secolo 1 & 2	Dry Steam	120.00
Italy	Nuova Larderello	Dry Steam	20.00
<i>Italy Total</i>			<i>915.50</i>
Portugal (Azores)	Pico Alto	Binary	4.50
Portugal (Azores)	Pico Vermelho	Binary	13.50
Portugal (Azores)	Ribeira Grande	Binary	15.00
<i>Portugal (Azores) Total</i>			<i>33.00</i>
Romania	CE Iosia Nord	Binary	0.05
<i>Romania Total</i>			<i>0.05</i>
Russia	Mendeleevskaya	Single Flash	1.80
Russia	Mutnovskaya	Single Flash	62.00
Russia	Okeanskaya	Single Flash	3.60
Russia	Pauzhetskaya	Single Flash	14.50
Russia	Verkhnemutnovskaya		12.00
<i>Russia Total</i>			<i>93.90</i>
Turkey	Afjet	Binary	2.76
Turkey	Alasehir Zorlu	Double Flash	45.00
Turkey	Babadere 1	Binary	8.00
Turkey	Baklaci	Binary	19.40
Turkey	Buharkent	Binary	13.77
Turkey	Deniz (Maren 2)	Binary	24.00
Turkey	Dora 1 Unit 1	Binary	7.95
Turkey	Dora 2 Unit 1	Binary	9.50
Turkey	Dora 3 a	Binary	17.00
Turkey	Dora 3 b & Dora 4	Binary	34.00
Turkey	Efeler Unit 1	Double Flash	47.50
Turkey	Efeler Unit 2	Binary	22.50
Turkey	Efeler Unit 3	Binary	22.50

Turkey	Efeler Unit 4	Binary	22.00
Turkey	Efeler Unit 6	Binary	22.60
Turkey	Efeler Unit 7	Binary	25.00
Turkey	Efeler Unit 8	Binary	50.00
Turkey	Emirler 1	Binary	3.50
Turkey	Galip Hoca (Germencik)	Double Flash	47.40
Turkey	Greeneco 1 & 2	Binary	25.60
Turkey	Greeneco 6	Binary	26.00
Turkey	Gümüşköy 1 & 2	Binary	13.20
Turkey	Ida	Binary	11.75
Turkey	Incirlova	Binary	25.00
Turkey	Kemaliye	Binary	24.00
Turkey	Ken Kipas 1	Binary	24.00
Turkey	Ken Kipas 3	Binary	24.80
Turkey	Kiper Nazili	Binary	10.20
Turkey	Kizildere 2	Double Flash	15.00
Turkey	Kizildere 3	Double Flash	245.01
Turkey	Kizildere Bereket	Binary	6.85
Turkey	Kubilay	Binary	24.00
Turkey	Kuyucak	Binary	18.00
Turkey	Maren 1 (Irem)	Binary	20.00
Turkey	Maren 2 (Sinem)	Binary	24.00
Turkey	Maspo Ala 1	Binary	10.00
Turkey	Maspo Ala 2	Binary	30.00
Turkey	Mehmetan	Binary	24.80
Turkey	Melih	Binary	32.00
Turkey	Mis 1	Binary	12.30
Turkey	Mis 2	Binary	24.00
Turkey	Mis 3	Binary	48.00
Turkey	Neihe Beren	Binary	20.00
Turkey	Özmen 1	Binary	12.00
Turkey	Özmen 2	Binary	12.00
Turkey	Özmen 3	Binary	18.60
Turkey	Pamukören 1-5 (7)	Binary	176.50
Turkey	RSC Seferihisar	Binary	12.00
Turkey	Salihi 3 Sanko	Binary	30.00
Turkey	Sultanhisar 1	Binary	36.31
Turkey	Tosunlar 1	Binary	3.80
Turkey	Tuzla	Binary	7.50
Turkey	Tuzla JES 1	Binary	3.20
Turkey	Tuzla West	Binary	11.50
Turkey	Umurlu 2	Binary	12.00
<i>Turkey Total</i>			<i>1 518.30</i>
Europe Total			1 884.05
United States	Aidlin	Dry Steam	22.40
United States	Amedee	Binary	3.00
United States	Beowave	Double Flash	20.60
United States	Big Geysers	Dry Steam	138.00
United States	Blue Mountain	Binary	63.90
United States	Blundell	Single Flash	44.80
United States	Bottle Rock	Dry Steam	0.00
United States	Brady	Double Flash	21.50
United States	Calistoga	Dry Steam	97.00

United States	CE Leathers	Double Flash	45.50
United States	CE Turbo	Single Flash	11.50
United States	Cobb Creek	Dry Steam	110.00
United States	Coso Navy	Double Flash	272.20
United States	Del Ranch	Double Flash	45.50
United States	Desert Peak	Binary	26.00
United States	Dixie Valley	Double Flash	70.90
United States	Don A. Campbell	Binary	47.50
United States	Eagle Rock	Dry Steam	110.00
United States	Elmore	Double Flash	45.50
United States	Enel Salt Wells	Binary	23.60
United States	Galena 2	Binary	13.50
United States	Galena 3	Binary	30.00
United States	Geo East Mesa	Double Flash	51.20
United States	Grant	Dry Steam	118.00
United States	Heber 1	Double Flash	62.50
United States	Heber 2	Binary	19.00
United States	Heber SIGC	Binary	80.00
United States	Hudson Ranch I	Triple Flash	55.00
United States	Lake View	Dry Steam	118.00
United States	Lightning	Binary	4.00
United States	Mammoth Pacific I	Binary	10.00
United States	McCabe	Dry Steam	110.00
United States	McGinness Hills 3	Binary	74.00
United States	NCPA I	Dry Steam	110.00
United States	NCPA II	Dry Steam	55.00
United States	Neal Hot Springs	Binary	33.00
United States	North Brawley	Binary	80.00
United States	OIT	Binary	1.80
United States	Ormesa I	Binary	2.40
United States	Ormesa IE (retired)	Binary	14.40
United States	Ormesa IH (retired)	Binary	9.60
United States	Ormesa II	Double Flash	18.00
United States	Paisley	Binary	3.70
United States	Patua	Binary	48.00
United States	Quicksilver	Dry Steam	118.00
United States	Raft River	Binary	18.00
United States	Richard Burdette	Binary	30.00
United States	Ridgeline	Dry Steam	110.00
United States	RMOTC	Binary	0.30
United States	Salton Sea I	Single Flash	10.00
United States	Salton Sea IV	Double Flash	47.50
United States	Salton Sea V	Double Flash	58.30
United States	San Emidio	Binary	11.80
United States	Socrates	Dry Steam	118.00
United States	Soda Lake I	Binary	5.10
United States	Soda Lake II	Binary	18.00
United States	Sonoma	Dry Steam	78.00
United States	Steamboat Hills	Binary	21.80
United States	Steamboat II	Binary	18.20
United States	Steamboat III	Binary	18.20
United States	Stillwater	Binary	47.20
United States	Sulphur Springs	Dry Steam	113.00

United States	Thermo No. 1	Binary	14.00
United States	Tungsten Mountain	Binary	37.00
United States	Tuscarora	Binary	32.00
United States	Vulcan	Double Flash	39.60
United States	Whitegrass No. 1	Binary	6.40
United States (Alaska)	Chena Hot Springs	Binary	0.40
United States (Hawaii)	Puna (expansion)	Binary	16.00
<i>United States Total</i>			<i>3 327.30</i>
North America Total			3 327.30
Mexico	Cerro Prieto I	Single Flash	30.00
Mexico	Cerro Prieto II	Double Flash	220.00
Mexico	Cerro Prieto III	Double Flash	110.00
Mexico	Domo San Pedro	Single Flash	25.50
Mexico	Les Tres Virgenes	Single Flash	10.00
Mexico	Los Azufres U-14	Single Flash	26.50
Mexico	Los Azufres U-15	Single Flash	26.50
Mexico	Los Azufres U-16	Single Flash	26.50
Mexico	Los Azufres U-17 AZIII-1 (Ph I)	Single Flash	50.00
Mexico	Los Azufres U-18 AZIII (Ph 2)	Single Flash	27.00
Mexico	Los Azufres U-2	Back Pressure	5.00
Mexico	Los Humeros II & III	Single Flash	80.20
Mexico	Los Humeros U-3	Back Pressure	5.00
Mexico	Los Humeros U-6	Back Pressure	5.00
Mexico	Los Humeros U-8	Back Pressure	5.00
<i>Mexico Total</i>			<i>652.20</i>
Chile	Cerro Pabellon	Binary	48.00
<i>Chile Total</i>			<i>48.00</i>
Colombia	Las Maracas	Binary	0.10
<i>Colombia Total</i>			<i>0.10</i>
Costa Rica	Las Paillas I	Binary	42.50
Costa Rica	Las Paillas II	Single Flash	55.00
Costa Rica	Miravalles	Single Flash	161.50
<i>Costa Rica Total</i>			<i>259.00</i>
El Salvador	Ahuachapan	Single Flash	95.00
El Salvador	Berlin	Single Flash	109.40
<i>El Salvador Total</i>			<i>204.40</i>
Guatemala	Amatitlan	Binary	25.00
Guatemala	Zunil	Binary	28.00
<i>Guatemala Total</i>			<i>53.00</i>
Honduras	Platanares	Binary	38.00
<i>Honduras Total</i>			<i>38.00</i>
Nicaragua	Momotombo	Single Flash	42.00
Nicaragua	San Jacinto-Tizate	Back Pressure	72.00
<i>Nicaragua Total</i>			<i>114.00</i>
Central & South America Total			1 368.70
China	Yangbajing	Double Flash	24.18
China	Yangyi, Tibet	Binary	16.00
<i>China Total</i>			<i>40.18</i>
Indonesia	Darajat	Dry Steam	270.00
Indonesia	Dieng Unit 1	Single Flash	60.00
Indonesia	Kamojang	Single Flash	3.00
Indonesia	Kamojang Unit 3	Dry Steam	55.00

Indonesia	Kamojang Unit 4	Dry Steam	60.00
Indonesia	Kamojang Unit 5	Dry Steam	35.00
Indonesia	Karaha Bodas	Dry Steam	30.00
Indonesia	Lahendong - Binary	Binary	0.50
Indonesia	Lahendong Unit 1 and 2	Single Flash	40.00
Indonesia	Lahendong Unit 3 and 4	Single Flash	40.00
Indonesia	Lahendong Unit 5 and 6	Single Flash	40.00
Indonesia	Lumut Balai	Single Flash	55.00
Indonesia	Mataloko	Single Flash	2.50
Indonesia	Muara Laboh	Double Flash	85.30
Indonesia	Patuha Unit 1	Single Flash	55.00
Indonesia	Salak	Single Flash	376.80
Indonesia	Sarulla	Binary	330.00
Indonesia	Sibayak	Back Pressure	12.00
Indonesia	Sorik Marapi Unit 1 - 2	Binary	90.00
Indonesia	Ulubelu Unit 1 and 2	Single Flash	110.00
Indonesia	Ulumbu Unit 3 and 4 (APBN)	Single Flash	5.00
Indonesia	Wayang Windu Unit 1	Single Flash	110.00
		<i>Indonesia Total</i>	<i>1865.10</i>
Japan	Goto-en	Binary	0.09
Japan	Hachijo-jima	Single Flash	3.30
Japan	Hagenoyu	Binary	2.00
Japan	Hatchobaru 2	Double Flash	56.00
Japan	Iwate Chinetsu	Single Flash	7.50
Japan	Kakkonda 1	Single Flash	50.00
Japan	Kirishima Kokusai Hotel	Binary	0.10
Japan	Kuju Kanko Hotel	Single Flash	0.99
Japan	Matsukawa	Dry Steam	23.50
Japan	Mori	Double Flash	50.00
Japan	Ogiri / Ohgiri	Single Flash	30.00
Japan	Oguni Matsuya	Binary	0.06
Japan	Onikobe	Single Flash	12.50
Japan	Otake	Single Flash	12.50
Japan	Sichimi Spring	Binary	0.02
Japan	Sugawara	Binary	5.00
Japan	Suginoi Hotel	Single Flash	1.90
Japan	Sumikawa	Single Flash	50.00
Japan	Takigami	Single Flash	30.05
Japan	Tsuchiyo	Binary	0.40
Japan	Uenotai	Single Flash	28.80
Japan	Waita	Binary	2.00
Japan	Wasabizawa	Double Flash	46.00
Japan	Yamagawa	Single Flash	30.00
Japan	Yanaizu-Nishiyama	Single Flash	65.00
Japan	Yumura Spring	Binary	0.03
		<i>Japan Total</i>	<i>507.74</i>
Philippines	Bacman I	Single Flash	120.00
Philippines	Bacman II	Single Flash	20.00
Philippines	Maibarara	Single Flash	32.00
Philippines	Maibarara	Single Flash	32.00
Philippines	Mak-Ban A	Double Flash	126.40
Philippines	Mak-Ban B	Double Flash	126.40
Philippines	Makban Binary	Binary	15.80

Philippines	Mak-Ban Binary	Binary	15.70
Philippines	Mak-Ban C	Single Flash	110.00
Philippines	Mak-Ban D	Single Flash	40.00
Philippines	Mak-Ban E	Single Flash	40.00
Philippines	Malitbog	Single Flash	232.50
Philippines	Malitbog bottoming cycle	Single Flash	16.70
Philippines	Mount Apo	Single Flash	108.48
Philippines	Northern Negros	Single Flash	0.00
Philippines	Palinpinon	Single Flash	112.50
Philippines	Palinpinon II	Single Flash	109.00
Philippines	Tiwi A	Single Flash	120.00
Philippines	Tiwi B	Single Flash	0.00
Philippines	Tiwi C	Single Flash	114.00
Philippines	Tongonan I	Double Flash	132.00
Philippines	Upper Mahiao	Binary	136.48
		<i>Philippines Total</i>	<i>1 759.96</i>
Taiwan	Cingshuei	Binary	0.30
Taiwan	Quingshui	Binary	4.20
		<i>Taiwan Total</i>	<i>4.50</i>
Thailand	Fang	Binary	0.30
		<i>Thailand Total</i>	<i>0.30</i>
		Asia total	4 177.78
Australia	Birdsville	Binary	0.00
Australia	Winton	Binary	0.30
		<i>Australia Total</i>	<i>0.30</i>
New Zealand	K24	Binary	8.30
New Zealand	Kawerau	Double Flash	100.00
New Zealand	Mokai 1	Single Flash	55.00
New Zealand	Nga Awa Purua	Triple Flash	140.00
New Zealand	Ngatamariki	Binary	82.00
New Zealand	Ngawha	Binary	10.00
New Zealand	Ngawha 2	Binary	15.00
New Zealand	Ngawha 3	Binary	31.50
New Zealand	Ohaaki	Single Flash	47.00
New Zealand	Poihipi	Single Flash	55.00
New Zealand	Rotokawa	Single Flash	34.00
New Zealand	Tasman BP	Back Pressure	5.00
New Zealand	Tauhara	Binary	26.00
New Zealand	Te Ahi O Maui	Binary	25.00
New Zealand	Te Mihi	Double Flash	166.00
New Zealand	TG1	Binary	0.00
New Zealand	TG2	Binary	0.00
New Zealand	Topp2	Binary	23.00
New Zealand	Wairakei	Double Flash	115.00
New Zealand	Wairakei Binary	Binary	15.00
		<i>New Zealand Total</i>	<i>952.80</i>
Papua New Guinea	Lihir	Back Pressure	56.00
		<i>Papua New Guinea Total</i>	<i>56.00</i>
		Oceania Total	1 009.10
Ethiopia	Aluto-Langano	Binary	7.30
		<i>Ethiopia Total</i>	<i>7.30</i>
Kenya	Eburru	Single Flash	2.50

Kenya	OLK 01 & 12, 13	Single Flash	15.00
Kenya	OLK 02 and 03	Single Flash	12.80
Kenya	OLK 04 - 08	Single Flash	27.80
Kenya	OLK 09 and 10	Single Flash	10.00
Kenya	OLK 11	Single Flash	5.00
Kenya	OLK 14	Single Flash	5.00
Kenya	OLK 15	Single Flash	5.00
Kenya	Olkaria I Au	Single Flash	150.60
Kenya	Olkaria I Unit 1-3	Single Flash	45.00
Kenya	Olkaria II - Units 1-3	Single Flash	105.00
Kenya	Olkaria III	Binary	150.00
Kenya	Olkaria IV - Units 1 and 2	Single Flash	149.80
Kenya	Olkaria V - Units 1 and 2	Single Flash	173.20
Kenya	Oserian 202	Binary	2.00
Kenya	Oserian 306	Back Pressure	2.00
<i>Kenya Total</i>			<i>860.70</i>
Africa total			868.00
World Total			12 634.93



Figure C - 1. Geothermal power plants locations worldwide [48].

Appendix D

Table D - 1. Large systems for heating and cooling other than DH, in 2018 [49].

Country	No	GE. capacity installed	Production
		[MW _{th}]	[GWh _{th} /yr]
Austria	1	17.0	69.6
Bosnia-Herzegovina	<500	-	-
Czech Republic	1	6.6	21.0
Denmark	1	50.0	-
France	15	> 34.0	130 774.0
Germany	6	60.1	484.2
Hungary	38	77.2	83.1
Italy	1	4.4	-
Netherlands	19	195.41	941.0
Norway	3	-	-
Poland	1	9.0	-
Slovakia	76	406.0	452.0

Table D - 2. GSHPs in Europe in 2018 and predictions for 2020 [49].

Country	No		Capacity [MW _{th}]		Production [GWh _{th} /yr]	
	2018	2020	2018	2020	2018	2020
Austria	3 600	-	1 053	1 100	2 500	2 700
Belarus	260	260	10	10.5	7	7.50
Belgium	27 562	30 063	363	389.6	544.4	626.5
Bosnia- Herzegovina	<500	-	-	-	-	-
Bulgaria	8	-	5.52	-	14.75	-
Cyprus	175	1	10.2	1.4	19	2.65
Czech Republic	24 304	26 000	-	-	-	-
Denmark	<62 000	<62 000	-	-	4 - 6	-
Finland	148 000	-	100 - 150	-	6 000	-
France	213 500	330 000	2 050	2 640	3 360	4 488
Germany	405 500	-	4 650	-	9 025	-
Greece	3 600	3 500	184	195	383	450
Hungary	7 000	8 000	78	88	144	176
Ireland	18 242	18 815	202.5	209	260.26	270.67
Italy	15 800	-	745	-	906	-
Lithuania	8 729	9 964	110.2	125.5	255	290
Macedonia	>500	-	1.25	-	10.5	-
The Netherlands	59 652	66 000	1 482	1 700	1 526	1 850
Norway	58 000	65 000	1 099	1 270	4 103	5 080
Poland	61 660	74 000	725	860	860	1 140
Portugal	54	-	0.65	-	0.87	-
Romania	347	600	21	40	40	100
Serbia	1 055	-	15 590.88	-	34 366	-
Slovenia	12 710	13 650	209.5	230	260.62	324
Spain	-	-	289	368	-	-
Sweden	593 990	605 000	6 772	6 750	22 950	25 000
Switzerland	104 973	112 000	2 157.2	2 270	3 610.4	4 300
Turkey	146	150	108.82	120	880.38	1 052
UK	31 800	570	936	37 800	680	1 224
Ukraine	1 550	-	-	-	-	-

Table D - 3. Geothermal heat in agriculture and industry [49].

Country	Capacity [MW _{th}]		Production [GWh _{th} /yr.]	
	2020	2025	2020	2025
Croatia	6.5	10.0	10.9	20
France	30.0	30.0	-	-
Greece	63.1	71.1	82.9	96
Hungary	365.0	380.0	832.0	867
Lithuania	18.0	18.0	-	18
The Netherlands	313.0	429.0	2 035.0	2 789
Poland	6.0	9.0	8.0	12
Serbia	8 494.0	20 120.0	74 377.0	136 870
Switzerland	2.0	16.0	16.0	128
Turkey	1 200.0	1 600.0	4 244.0	5 660
UK	-	2.0	-	14

Table D - 4. Geothermal heat for buildings [49].

Country	Capacity [MW _{th}]		Production [GWh _{th} /yr]	
	2020	2025	2020	2025
Belgium	-	7.0	-	11.0
Croatia	12.6	20.0	12.1	30.0
Greece	1.7	1.7	2.9	2.9
Hungary	80.0	90.0	83.0	95.0
Serbia	5 422.0	22 262.0	47 484.0	125 473.0
Turkey	120.0	150.0	525.0	656.0

Table D - 5. Geothermal heat in balneology and other [49].

Country	Capacity [MW _{th}]		Production [GWh _{th} /yr]	
	2020	2025	2020	2025
Croatia	24.0	30.0	15.3	30.0
Greece	43.0	43.0	71.4	71.4
Hungary	253.0	263.0	757.0	787.0
Lithuania	10.0	13.0	13.0	16.0
Portugal	-	20.0	-	111.0
Serbia	1 824.0	38 546.0	15 975.0	202 232.0
Switzerland	23.2	23.2	192.8	192.8
Turkey	1 400.0	1 700.0	7 300.0	8 900.0
UK	-	0.6	-	3.0

Appendix E

Table E - 1. Comparison between the economic potential by country suggested by [16], [42].

Country	Limberger et al., 2014						van Wees et al., 2013					
	2020	2030	2050	2020*	2030*	2050*	2020*	2030*	2050	2020	2030	2050
	[GWe]	[GWe]	[GWe]	[TWh]	[TWh]	[TWh]	[GWe]	[GWe]	[GWe]	[TWh]	[TWh]	[TWh]
Austria	0.12	0.22	11.00	0.95	1.73	86.72	-	0.013	-	-	0.10	-
Belarus	-	-	2.00	-	-	15.77	-	-	-	-	-	-
Belgium	-	-	4.00	-	-	31.54	-	-	-	-	-	-
Bosnia-Herz.	0.09	0.11	5.00	0.71	0.87	39.42	-	-	-	-	-	-
Bulgaria	-	-	13.00	-	-	102.49	-	0.013	-	-	0.10	-
Croatia	0.98	0.87	7.00	7.73	6.86	55.19	-	0.381	-	-	3.00	-
Czech Republic	-	-	7.00	-	-	55.19	-	0.005	-	-	0.04	-
Denmark	-	-	5.00	-	-	39.42	-	0.004	-	-	0.03	-
Estonia	-	-	-	-	-	-	-	0.005	-	-	0.04	-
Finland	-	-	2.00	-	-	15.77	-	-	-	-	-	-
France	0.34	0.96	99.00	2.68	7.57	780.52	0.381	0.955	82.83	3.00	7.53	653.02
Germany	1.22	1.99	53.00	9.62	15.69	417.85	1.257	1.979	43.83	9.91	15.60	345.59
Greece	0.39	0.37	15.00	3.07	2.92	118.26	1.196	0.204	10.31	9.43	1.61	81.30
Hungaria	4.74	4.04	24.00	37.37	31.85	189.22	0.052	2.164	22.03	0.41	17.06	173.69
Ireland	-	-	-	-	-	-	0.074	0.075	3.46	0.58	0.59	27.26
Iceland	16.30	14.30	43.00	128.51	112.74	339.01	0.736	9.348	40.83	5.80	73.70	321.89

(Continuation)

Ireland	-	-	5.00	-	-	39.42	-	-	-	-	-	-
Italy	2.77	2.54	36.00	21.84	20.03	283.82	0.856	1.531	28.64	6.75	12.07	225.83
Latvia	-	-	1.00	-	-	7.88	-	0.001	0.36	-	0.01	2.84
Lithuania	-	0.05	4.00	-	0.39	31.54	-	0.005	2.37	-	0.04	18.71
Luxembourg	-	-	-	-	-	-	-	-	0.34	-	-	2.66
Macedonia	-	-	2.00	-	-	15.77	-	-	-	-	-	-
Moldova	-	-	2.00	-	-	15.77	-	-	-	-	-	-
The Netherlands	0.36	0.52	7.00	2.84	4.10	55.19	-	0.029	6.57	-	0.23	51.76
Norway	-	-	8.00	-	-	63.07	-	-	-	-	-	-
Poland	0.03	0.13	29.00	0.24	1.02	228.64	-	-	18.21	-	-	143.56
Portugal	-	-	10.00	-	-	78.84	0.057	0.049	8.00	0.45	0.39	63.00
Romania	0.15	0.23	22.00	1.18	1.81	173.45	-	0.022	13.27	-	0.17	104.65
Serbia	0.64	0.66	14.00	5.05	5.20	110.38	-	-	-	-	-	-
Slovakia	0.42	0.48	8.00	3.31	3.78	63.07	0.004	0.113	6.92	0.03	0.89	54.57
Slovenia	0.04	-	2.00	0.32	-	15.77	-	0.001	1.03	-	0.01	8.15
Spain	0.28	0.39	59.00	2.21	3.07	465.16	0.038	0.066	44.21	0.30	0.52	348.58
Sweden	-	-	14.00	-	-	110.38	-	-	-	-	-	-
Switzerland	-	0.16	6.00	-	1.26	47.30	0.022	0.143	5.45	0.17	1.13	42.90
Turkey	15.80	14.50	135.00	124.57	114.32	1 064.34	-	7.903	122.52	-	62.31	965.90
Ukraine	0.13	0.24	27.00	1.02	1.89	212.87	-	-	-	-	-	-
United Kingdom	0.03	0.05	15.00	0.24	0.39	118.26	0.036	0.055	5.30	0.28	0.43	41.80
Total	44.83	42.81	696.00	353.44	337.51	5 487.26	4.71	25.06	466.49	37.12	197.60	3 677.66

* calculate value, considering a yearly load factor of 7884 hours, deduced from prediction of van Wees et al. [16] for 2050.

Table E - 2. Projected geothermal power and Economic potential [16].

Country		Gross Geothermal Electricity Generation	Geothermal Electricity Target in the NREAP	Geothermal Economic Potential	Geothermal Economic Potential	Share of geothermal in gross electricity production	Geothermal Economic Potential - Installed Capacity
		[TWh]	[TWh]	[TWh]	[TWh]	[%]	[MW _e]
		2010	2020	2030		2050	
Austria		0.002	0.002	0.100	67.100	69.0	8 511.0
Belgium		-	0.002	-	22.280	17.0	2 826.0
Bulgaria		-	-	0.100	71.660	112.0	9 089.0
Croatia		-	-	3.000	49.970	-	6 338.0
Czech Republic		-	0.002	0.040	30.680	26.0	3 891.0
Denmark		-	-	0.030	29.430	55.0	3 732.0
Estonia		-	-	0.040	1.670	9.0	212.0
France	Actual/projected	0.153	0.475	-	-	-	-
	≤300 EUR/MWh	-	3.000	-	-	-	-
	≤200 EUR/MWh	-	0.010	7.530	-	-	-
	≤150 EUR/MWh	-	-	0.390	-	-	-
	≤100 EUR/MWh	-	-	-	653.020	83.0	82 828.0
Germany	Actual/projected	0.027	1.650	-	-	-	-
	≤300 EUR/MWh	-	9.910	-	-	-	-
	≤200 EUR/MWh	-	0.280	15.600	-	-	-
	≤150 EUR/MWh	-	-	1.370	-	-	-
	≤100 EUR/MWh	-	-	-	345.590	40.0	43 834.0

(Continuation)

Greece	Actual/projected	-	0.073	-	-	-	-
	≤300 EUR/MWh	-	9.430	-	-	-	-
	≤200 EUR/MWh	-	0.080	1.610	-	-	-
	≤150 EUR/MWh	-	-	0.470	-	-	-
	≤100 EUR/MWh	-	-	-	81.300	103.0	10 312.0
Hungary		-	0.410	17.060	173.690	338.0	22 031.0
Ireland	Actual/projected	-	0.035	-	-	-	-
	≤300 EUR/MWh	-	0.580	-	-	-	-
	≤200 EUR/MWh	-	0.060	0.590	-	-	-
	≤150 EUR/MWh	-	-	0.190	-	-	-
	≤100 EUR/MWh	-	-	-	27.260	69.0	3 457.0
Italy		5.630	6.750	12.070	225.830	54.0	28 644.0
Latvia		-	-	0.010	2.840	31.0	360.0
Lithuania		-	-	0.040	18.710	236.0	2 374.0
Luxembourg		-	-	-	2.660	42.0	337.0
Poland		-	-	-	143.560	66.0	18 210.0
Portugal	Actual/projected	0.160	0.480	-	-	-	-
	≤300 EUR/MWh	-	0.450	-	-	-	-
	≤200 EUR/MWh	-	0.030	0.390	-	-	-
	≤150 EUR/MWh	-	-	0.160	-	-	-
	≤100 EUR/MWh	-	-	-	63.000	85.0	8 000.0
Romania		-	-	0.170	104.650	125.0	13 274.0
Slovakia		-	0.030	0.890	54.570	142.0	6 922.0
Slovenia		-	-	0.010	8.150	36.0	1 033.0
Spain		-	0.300	0.520	348.580	84.0	44 214.0
The Netherlands		-	-	0.230	51.760	32.0	6 565.0

(Continuation)

United Kingdom	Actual/projected	-	-	-	-	-	-
	≤300 EUR/MWh	-	0.280	-	-	-	-
	≤200 EUR/MWh	-	-	0.430	-	-	-
	≤150 EUR/MWh	-	-	0.020	-	-	-
	≤100 EUR/MWh	-	-	-	41.800	8.0	5 303.0
Iceland		4.500	5.800	73.700	321.890	-	40 829.0
Switzerland	Actual/projected	-	-	-	-	-	-
	≤300 EUR/MWh	-	0.170	-	-	-	-
	≤200 EUR/MWh	-	-	1.130	-	-	-
	≤150 EUR/MWh	-	-	-	-	-	-
	≤100 EUR/MWh	-	-	-	42.900	-	5 448.0
Turkey		0.700	-	62.310	965.900	-	122 515.0

Table E - 3. Historical geothermal power installed capacity [7].

COUNTRY	1990	1995	2000	2005	2010	2013	2015	2022
	[MWe]	[MWe]	[MWe]	[MWe]	[MWe]	[MWe]	[MWe]	[MWe]
Austria				1.00	1.40	1.40	1.20	1.40
Belgium								4.50
Croatia								17.50
France (Guadeloupe & Alsace)	4.20	4.20	4.20	15.00	16.00	17.00	16.00	17.7
Germany				0.20	6.60	11.90	27.00	48.95
Hungary								3.35
Iceland	44.60	50.00	170.00	322.00	575.00	664.40	665.00	753.9
Italy	545.00	631.70	785.00	790.00	843.00	875.50	916.00	915.5
Portugal (Azores)	3.00	5.00	16.00	16.00	29.00	28.50	28.00	33
Romania							0.10	0.05
Russia	11.00	11.00	23.00	79.00	82.00	81.90	82.00	93.9
Turkey	20.60	20.40	20.40	20.40	82.00	166.60	397.00	1518.3
Total Europe	628.40	722.30	1 018.60	1 243.60	1 635.00	1 847.20	2 132.30	3408.05
Growth [%]	14.943	41.0217	22.0891	31.47314	12.9786	15.43417	59.8298	
Argentina	0.70	0.60						
Australia		0.20	0.20	0.20	1.10	1.00	1.10	
China	19.20	28.80	29.20	28.00	24.00	27.00	27.00	
Costa Rica		55.00	142.50	163.00	166.00	207.10	207.00	
El Salvador	95.00	105.00	161.00	151.00	204.00	204.40	204.00	
Ethiopia			8.50	7.00	7.30	8.00	7.30	
Guatemala		33.40	33.40	33.00	52.00	48.00	52.00	
Indonesia	144.80	309.80	589.50	797.00	1 197.00	1 341.00	1 340.00	

(Continuation)

Japan	214.60	413.70	546.90	535.00	536.00	537.00	519.00
Kenya	45.00	45.00	45.00	127.00	167.00	248.50	594.00
Mexico	700.00	753.00	755.00	953.00	958.00	1 017.40	1 017.00
New Zealand	283.20	286.00	437.00	435.00	628.00	842.60	1 005.00
Nicaragua	35.00	70.00	70.00	77.00	88.00	149.50	159.00
Papua New Guinea				39.00	56.00	56.00	50.00
Philippines	891.00	1 227.00	1 909.00	1 931.00	1 904.00	1 848.00	1 870.00
Taiwan							0.10
Thailand	0.30	0.30	0.30	0.30	0.30	0.30	0.30
USA	2 774.60	2 816.70	2 228.00	2 544.00	3 093.00	3 389.00	3 450.00
Total worldwide	5 831.80	6 866.80	7 974.10	9 064.10	10 716.70	11 772.00	12 635.10

Table E - 4. Background and NREAPs targets for 2030 [16], [74], [75].

Country	Background	NREAPs - 2030 targets
Austria	3 geothermal CHP. FiT €0.07/kWh	2 PJ of electricity & DH
Belgium	Deep GE in Balmatt (Flanders). Project under development: Mons basin (Wallonia).	Electricity: 594 GWh Deep GE: 233 GWh GSHPs: 1 507 GWh
Bulgaria	Lack of data from drilling activities. FiT not applicable in practice.	Electricity: 407 GWh GSHPs: 1 419 GWh
Croatia	Plant operating + projects under development in Podravina and Bjelovar-Bilogora. FiT: €0.0159/kWh+15% bonus	Electricity: 17 MW / 129 GWh Heating & cooling: 437 GWh
Cyprus		GE in heating sector: 0.05%
Czech Republic	EGS resear project for CHP in Litomerice (North West). CHP under investigation in Semily and Liberec (Northern Bohemia). FiT: € 0.018/kWh or Bonus €0.014/kWh	Electricity: 10MW/112.3 GWh Heating and cooling 447 GWh GSHPs: 3 352.6 GWh
Denmark	Heat plants developed + 12 under investigation. Legal framework.	DH: 32 MW
Estonia	Developing research roadmap and potential analyses taken.	-
France	3 power plants operating, 1 EGS. 8 research permits awarded in Alsace + 2 in the Pyrenees + 5 in the Massif Central. 2 research permits given in Massif Central. Regulatory framework. Risk insurance. FiT €0.020/kWh +Bonus (mainland) < €0.08/kWh /(overseas) < €0.13/kWh + (overseas) €0.03/kWh premium	Electricity: 24MW Deep GE: $(4-5.2) \cdot 10^3$ GWh GSHPs: $(5-7) \cdot 10^3$ GWh
Germany	Plants in operation. 2 EGS (Landau & Insheim) only commercially available in the World. Projects either under development or exploration. 28 geoth projects under investigation, including 4 EGS. Favourable framework.	Negligible and no growth expected
Greece	13 projects investigated.	Electricity: 100MW / 600GWh (geothermal heat for power generation 542ktoe)
Hungary	Power plant models developed. ESG commissioned. Complicated legal framework.	GE: 1 356 GWh
Ireland	Sector progress very slow. Seismic surveys at the Newcastle project and planning permission for the first deep geothermal electricity plant.	
Italy	> 130 for exploration and exploitation. 50 research permits granted. Including areas outside Tuscany. FiT + Fi premium + Tender system. Administrative procedures extremely long.	Electricity: 950MW / 7 100MWh Heat: 17 445MWh
Latvia	EGS pilot project in the Baltic States. Poor information about geothermal resources.	
Lithuania		
Luxembourg	There are no deep geothermal projects in operation or under evaluation.	GSHPs: 422GWh.
Malta		Research stage

The Netherlands	Very dynamic market for geothermal heat. Mining Act adapted to geothermal. Lot of geological data. Nine deep geothermal installations; two new projects started in 2013; more than 70 licences requested.	Deep GE: 6 666.7 GWh.
Poland	R&D work on prospects for binary and EGS. No framework.	Heating & cooling: 366GWh
Portugal	Successfully working in Azores. Concession rights for exploration of geothermal resources. Expansions in Azores. 12 MW EGS examined.	Electricity: 60 MW.
Romania	Specific measures established. Specific regulatory framework.	
Slovakia	Heat plants in operation. Power project under development and another under planning, (Kosice)	Electricity: 4MW/30GWh Deep GE: 581.5GWh GSHPs: 372.2GWh
Slovenia	Investigation potential for geothermal electric power production in the Pomurje. Purchase price €0.1524/kWh or bonus €0.1036/kWh	
Spain	Geological risk important barrier.	Electricity: 30MW
United Kingdom	Power projects under development (the Eden project and the United Downs Deep Geothermal project both in Cornwall). CfD <0.1765/kWh.	
Switzerland	FiT: €0.1889/kW - €0.3330/kW	Deep geothermal energy plays a key role in 2050
Turkey	Exploration activities. Law of Geothermal Resources and Natural Mineral Waters and its Implementation Regulation. FiT.	