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A prospective study on the geothermal potential in the EU

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PROSPECTIVE STUDY ON THE GEOTHERMAL ELECTRICITY POTENTIAL IN THE EU IN 2020/2030/2050

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The GEOELEC project - *Developing Geothermal Electricity in Europe to have a renewable energy mix* - is dedicated to the promotion of geothermal electricity production in the EU, including combined heat and power (see Preliminary Chapter on geothermal electricity production).

The project is financed by the program Intelligent Energy – Europe (IEE) and led by the European Geothermal Energy Council (EGEC) through a consortium of 10 partners.

Executive Summary

Geothermal power generation has its roots in Europe, where the first test in 1904 and the real beginning of power generation in 1913 took place, both at the Larderello dry steam field in Italy. Since then, the development of geothermal technology has been slow but continuous and the total installed capacity currently amounts to 0.9 gigawatts (GWe) in the European Union (EU) (and 1.8 GWe in the whole of Europe), generating approximately 6TWh of electric power every year (11.7 TWh including Iceland and Turkey).

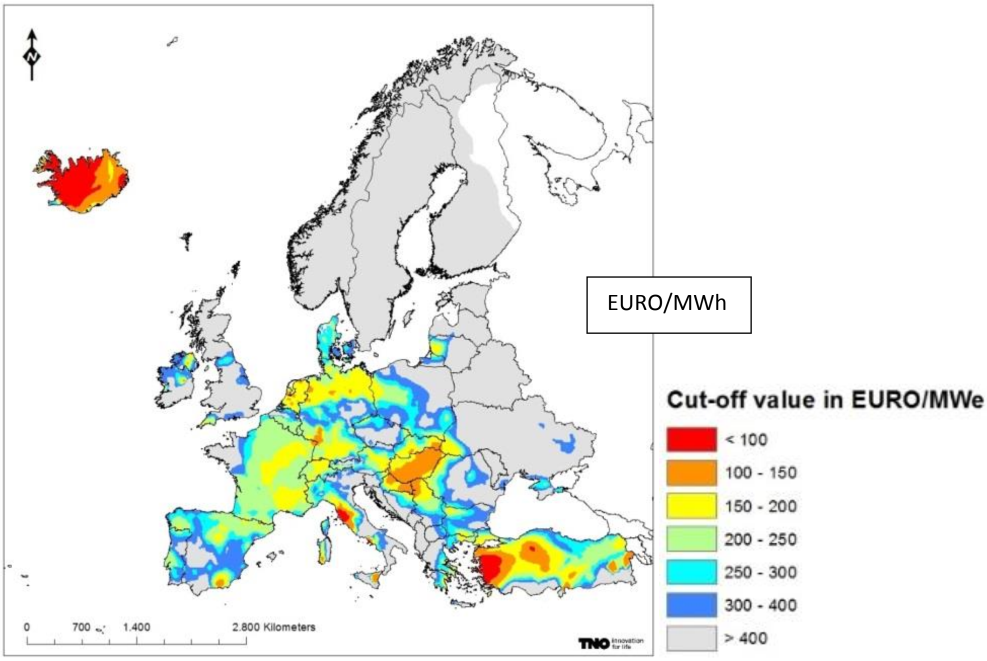
For a decade, thanks to the optimisation of the new binary system technology, geothermal electricity can be produced using lower temperatures. Moreover, with Enhanced Geothermal Systems (EGS), a breakthrough technology proven since 2007, geothermal power can in theory be produced anywhere in Europe.

According to the trajectories set out in the National Renewable Energy Action Plans (NREAPs) of the EU Member States, the capacity will grow from 0.9 GWe installed in 2013 to 1.4 GWe in 2020. The production of geothermal electricity in 2020 is forecasted to be 11 TWh. However, the actual potential is much larger.

Whilst some Member States acknowledge the possibility of developing geothermal power in their NREAPs, many others simply did not carry out any study to assess the geothermal potential. Indeed, information utilised in locating and estimating the geothermal resource and potential is scattered in different ministries, universities, national institutes, oil & gas companies and various private entities. This resulted in very conservative targets for geothermal power.

With the present study the GEOELEC project aims to make the first step to fill the existing gap. The resource assessment is the product of the integration and interpretation of existing data provided by the EU-28 countries and a newly defined methodology building on Canadian, Australian, and American methodology. The geological potential (heat in place) has been translated to an economical potential, using a Levelised Cost of Energy (LCoE) value of less than 150 EUR/MWh for the 2030 scenario and less than 100 EUR/MWh for the 2050 scenario:

- **The total geothermal electricity potential in the EU-28 is 21,2 TWh for the year 2020;**
- **In 2030 this amounts to 34 TWh;**
- **Thanks to economies of scale, innovative drilling concepts and substantial cost reduction, the economic potential in the EU grows to approximately 2570 TWh in 2050 and more than 4000 TWh including Iceland, Turkey and other European countries.**



Minimum levelized costs of Energy in 2030 (in EUR/MWh)

In order to realise and reap the all the benefits for the EU as a whole of the geothermal electricity potential stemming from this study, the GEOELEC project puts forward the following recommendations for policy-makers:

- **Create conditions to increase awareness about the advantages of this technology and its potential.** National Committees on Geothermal should be established in order to promote the technology to decision-makers, engaging the civil society and favour social acceptance. Additionally, a national committee can facilitate the implementation of the following 3 key actions:
    - Simplification of administrative procedure and quality
    - Training professionals
    - Dissemination of information

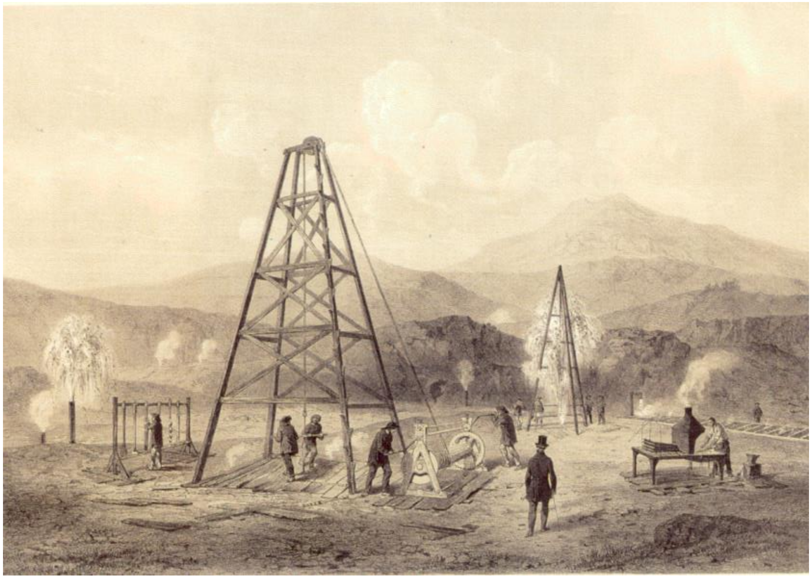
- In order to progress along the learning curve and deploy at large-scale a reliable renewable technology, **a European EGS flagship programme should be launched**, including new demonstration plants and test laboratories, notably in countries where there are not geothermal power plants in operation yet.

- **Establish the economic and financial conditions for geothermal development: a European Geothermal Risk Insurance Fund (EGRIF)** is an innovative option tailored to the specificities of geothermal to mitigate the cost of the geological risk and is a complementary tool to operational support, still needed to compensate for the long-standing lack of a level-playing field.

1. Background to geothermal electricity production

1.1 Technologies

Until a century ago, the exploitation of geothermal resources was primarily for leisure purpose; hot springs and geothermal baths. It was at the beginning of the 20th century that active exploitation of geothermal resources for electricity supply purposes was inaugurated. Successful production of electricity from geothermal heat was first achieved in Larderello, Italy, in 1904.



Geothermal bore-holes, Larderello, Tuscany, Italy.
Lithography of the mid-19th century.

Since this period, the production of geothermal electricity has steadily increased, though has been concentrated in areas where high temperature hydrothermal resources are available. The technological systems for geothermal electricity production can be subdivided in three large categories, which are also linked to the temperature ranges:

Minimum production temperature: 80°C - 150°C (Medium Enthalpy resources): this range of temperature is appropriate for use with binary plants (Organic Rankine or Kalina cycle), with typical power in the range 0.1-10 MWe. These systems are also suitable for heat & power co-generation, typically for single edifice to small towns heating;

Minimum production temperature: 150°C - 390°C (High Enthalpy resources): temperatures in this range can be exploited with dry steam, flash and hybrid plants, with typical power in the range

10-100 MWe. These systems also allow heat cogeneration for large towns' district heating. Above 200°C, these resources are generally limited to volcanic areas.

Minimum production temperature 390°C (Supercritical unconventional resources):

temperatures in this range, limited to volcanic areas, generally involve superheated dry steam plants, with power per unit volume of fluid up to one order of magnitude larger than conventional resources.

Besides the temperature range, the methods of exploitation can be further subdivided in two categories: conventional (dry steam and flash steam turbines) and low temperature (binary) geothermal electricity.

Conventional geothermal electricity: dry steam and flash steam turbines

Operating with large hydrothermal reservoirs at high temperature, i.e. above 150°C, such as those found in Tuscany (Italy) and Iceland, this technology has 100 years of history and is fully competitive today with a full cost of about 7€ct/kWh including systems costs and externalities.

> Flash: The high temperature, water at high pressure is brought to surface, where it is enters a low pressure chamber and 'flashes' into steam. The pressure created by this steam is channelled through a turbine, which spins to generate electrical power. Once the steam has exited the turbine, it is either released into the atmosphere as water vapour, or it cools back into liquid water and is injected back underground.
>
> Dry Steam: dry steam power plants utilise straight-forwardly steam which is piped from production wells to the plant, then directed towards turbine blades. Conventional dry steam turbines require fluids of at least 150°C and are available with either atmospheric (backpressure) or condensing exhausts.

Regrettably, it is very unlikely that new large geothermal reservoirs will be discovered in Europe. Therefore new projects need to be adapted to smaller and cooler resources.

Low temperature, hydrothermal geothermal electricity: Binary: ORC and Kalina Cycle

Binary, known also as organic Rankine cycle (ORC) or Kalina Cycle, plants operate usually with waters in the 100 to 180°C temperature range. Working fluid selection, in cooperation with beneficial conditions such as access to effective cooling, may allow power production from as low temperatures as 80°C.
In a binary system, the heat of water is transferred to a separate liquid with a lower boiling temperature. The separate liquid is called a 'working fluid'. When the hot geothermal water is brought to surface from deep underground, it is run through a 'heat exchanger' which transfers the heat from the geothermal water to the liquid working fluid. Because the working fluid boils at a low temperature, it vaporises readily with less geothermal heat, and this vaporization produces enough pressure to drive a turbine. What makes a binary system unique is that it operates as a two closed-loops (hence, binary); neither the geothermal water nor the working fluid are exposed to the surface environment. All the

water that is brought to surface has to be re-injected, and after vaporizing, the working fluid is cooled to its liquid state, so it may repeat the process. There are no-emissions in the binary geothermal cycle.

Beyond Hydrothermal: Enhanced Geothermal Systems – EGS

Geothermal energy has the potential to make a more significant contribution to the European electricity mix through the development of advanced technologies, especially the development of hot rock resources using enhanced geothermal system (EGS) techniques that would enable thermal energy recovery from outside of geological favourable regions.

An Enhanced Geothermal System (EGS) is an underground reservoir that has been created or improved artificially. The EGS concept is going to greatly increase geothermal potential as it allows for the production of geothermal electricity nearly anywhere in Europe with medium and low temperature.

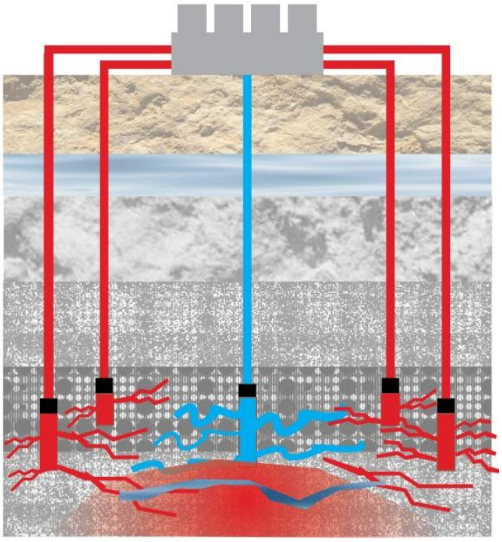


Figure: An Enhanced Geothermal System (EGS)

This concept involves:

- Using the natural fracture systems in the basement rocks
- Enlarging its permeability through stimulation
- Installing a multi-well system
- Through pumping and lifting, forcing the water to migrate through the fracture system of enhanced permeability ("reservoir") and use the heat for power production.

2.2 Benefits of geothermal electricity

A base load and flexible renewable energy source (no intermittency)…

BOX 1: Benefits of Geothermal Electricity

- ✓ A BASE LOAD AND FLEXIBLE RENEWABLE ENERGY SOURCE
- ✓ ENSURING PRICE STABILITY
- ✓ INCREASING SECURITY OF SUPPLY
- ✓ SCALABLE
- ✓ PROVIDING CLEAN ELECTRICTY
- ✓ OR COMBINED HEAT AND POWER
- ✓ AND SUPPORTING LOCAL AND SUSTAINABLE ECONOMIC DEVELOPMENT

Geothermal energy has many obvious qualities. A remarkable one is that it is not dependent on climate conditions as wind or solar energy may be. As a result, base load can be provided. Among all renewable energies, this makes geothermal one of the most reliable, as plants are able to operate up to 95 per cent of the time. Such a load factor makes geothermal competitive with fossil fuel and nuclear power plants.

But geothermal electricity is also flexible as it can be ramped up or down on demand, thereby contributing to the stability of the grid. Furthermore, geothermal plants can be productive for many years. Typically they have a 30 to 50 year life before the equipment wears out. Indeed the world's first geothermal power plant at Larderello, Italy was commissioned in 1913 and is still productive.

Ensuring price stability…

Developing and utilising geothermal resources for electricity can help to protect against volatile and rising electricity prices (Figure 1). The costs for fuels used to generate electricity influence the final price of the electricity produced. On the one hand, fossil fuels have traditionally been low priced, but their costs are increasing. On the other hand, the costs of geothermal power mainly depend on capital costs, as the fuel is free of charge and operation and maintenance costs are very limited. Emerging geothermal technologies hold significant potential for cost reduction and will reach full competitiveness in 2030.

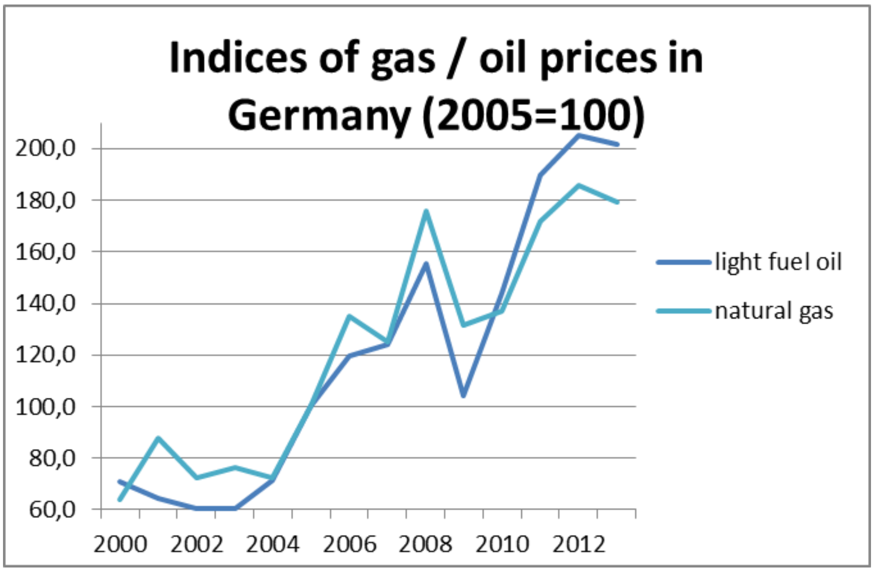


Figure: Development of energy prices in Germany (Source: Destatis)

Increasing security of supply…

As a renewable and domestic resource, geothermal enables a diversification of the electricity mix. Making use of this source reduces the amount of fuel that countries have to import and thereby increases their security of supply.

Scalable…

Geothermal power production is scalable. It is possible to have a very small geothermal project, for instance owned and run by a municipality, so it is necessary to have scale specific policies in place.

Providing Clean Electricity…

All mankind activities have an impact on nature. But compared to other energy sources, Geothermal has a negligible environmental footprint (see GEOLEC report "Environmental study on geothermal power"). Indeed, Geothermal power systems involve no combustion. Therefore they emit only a small amount of greenhouse gases and if one takes CO_2 as a benchmark, then geothermal closed-loop-binary plants emit 0 CO_2. Furthermore, Geothermal power plants produce only a small amount of air emissions compared to conventional fossil fuels and unlike other renewable energies such as solar or biomass, it has a very small land-use footprint.

Or Combined Heat and Power…

In a combined process the geothermal resources can be used for generating electricity and heat. Producing heat and electricity means optimising the efficiency factor of the energy production and upgrading cash flows. There are many types of direct use applications for the geothermal heat: greenhouses, aquaculture, industrial processes, agricultural processes, baths and spas, and district heating and cooling.

… And Supporting Local and Sustainable Economic Development

Using geothermal resources can provide economic opportunities for countries in the form of taxes, royalties, technology export and jobs. Because of specific geological conditions, these jobs require a thorough knowledge of the local conditions and cannot be exported. Therefore, investments in geothermal power can boost local economies and improve urban environment conditions alike.

2. Geothermal Resource Assessment in Europe

This chapter gives a definition for resource assessment and is a basis for a pan-European map based overview of the location of geothermal resources developed in the 2020, 2030 and 2050 timeline horizons for electricity production.

The resource assessment protocol is based on resource assessment concepts developed in the oil and gas industry, which have been adopted in an adjusted form for geothermal resource assessment and reporting. This protocol has been based on the following work:

- Beardsmore et al., 2010. A protocol for estimating and mapping the global EGS potential.
- AGEA, 2010. Australian code for reporting of exploration results, geothermal resources and geothermal reserves: the geothermal reporting code
- CanGEA, 2010. The Canadian geothermal code for public reporting

These documents describe a protocol to classify and estimate geothermal reserves and resources. Further, we used input from resource classification approaches developed in the oil and gas industry (Etherington et al., 2007).

In our approach we define in 3.2 the guidelines for estimating theoretical and technical potential for enhanced low permeability high enthalpy systems in detail for different stages in the workflow (play, lead, prospect, contingent resources, and reserves) for different play types.

2. 1 Basic definitions and best practices

McKelvey (Figure 3.1) and **project approach:** Key to resource assessment and classification is the concept of the McKelvey diagram (Figure 1), and a project oriented approach in which resources develop progressively from being inferred at an early exploration stage towards becoming discovered after drilling and finally economically recoverable at the production stage. In the exploration the transition from an inferred (undiscovered) to a discovered resource is determined by drilling the reservoir, which is capable to prove the occurrence of the resource and to appraise the productivity.

Play, leads and prospects (Figure 3.2): In the geothermal exploration workflow prior to drilling, the identification of a prospective reservoir location starts off with a so-called play concept. A geothermal **play** is a geographically (and in depth) *delimited area* where *specific subsurface conditions* allow to obtain sufficiently high flow rate of sufficiently high temperature, with suitable pressure and chemical conditions. A **lead** is a *particular subsurface reservoir* which has been identified by surface exploration studies (e.g. MT). A **prospect** is a location which has been studied thoroughly by surface exploration and has been earmarked to be drilled.

Conversion efficiency and power (Figure 3.4)

$Efficiency(\eta) = \frac{Tx - Ts}{Tx + Ts + 2 * 273.15K} \eta_c$

Tx = production temperature [C]

Ts = average surface temperature [C]

η_c= relative efficiency compared to carnot efficiency [-]

$Power\ (E) = \ Q\ \rho_{fluid}\ c_{fluid}(Tx - Tr)10^{-6}$ (in MW)

Q = flow rate [m3/s]

Tr = re-injection temperature [C]

$\rho_{fluid=}$ fluid density [kg/m3]

$c_{fluid=}$ fluid specific heat [J/kg/K]

The first equation is based on Tester et al. (2006) and Di Pippo (2008). Their analysis shows that for a large variety of conversion designs covering a spectrum from using produced steam directly to drive turbines (flash) as well as binary systems, that η_c= 0.6 (Figure 3.4).

For binary systems Tr is about 8°C above average surface temperature (Beardsmore et al., 2010).

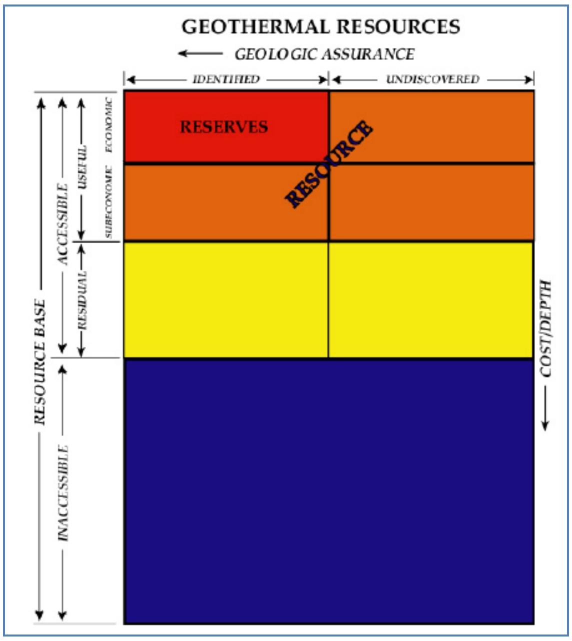


Figure: McKelvey diagram representing geothermal resource and reserve terminology in the context of geologic assurance and economic viability (from Williams et al., 2008)

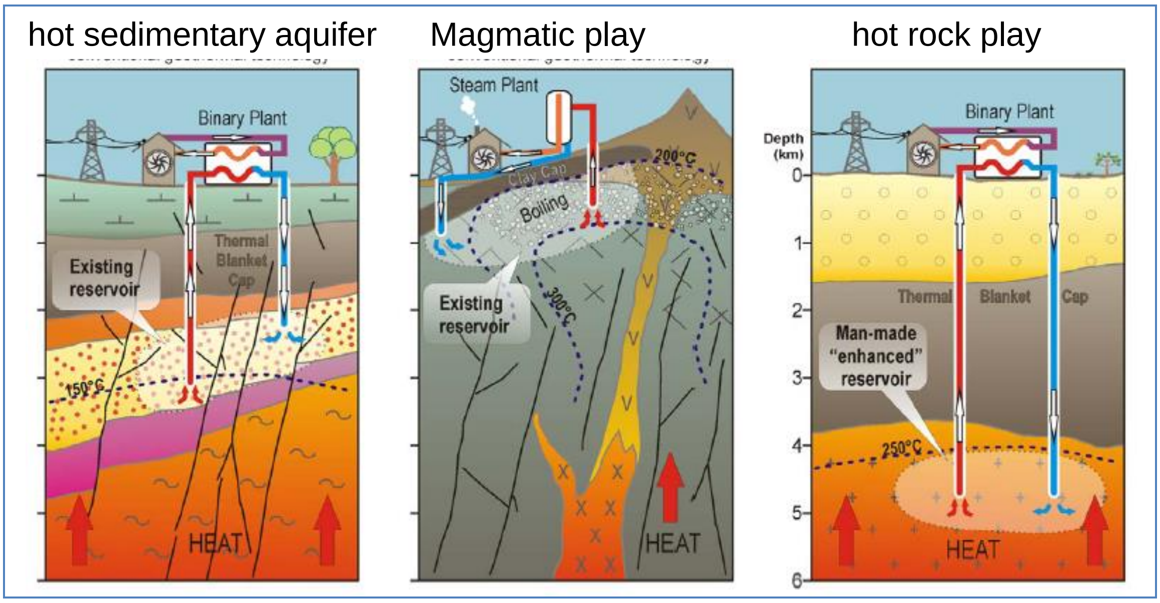


Figure: Example of different play types for geothermal systems (modified from Hot Rock ltd). Hot sedimentary aquifers and magmatic plays can be mostly developed without enhancing the reservoir, relying on natural aquifer and fracture permeability. Magmatic plays can generally produce very high temperatures at shallow depth. Low permeable rock plays are located in regions of elevated temperatures (caused by radiogenic heat production, elevated tectonic heat flow, or vertical heat advection trough deep fault zones).

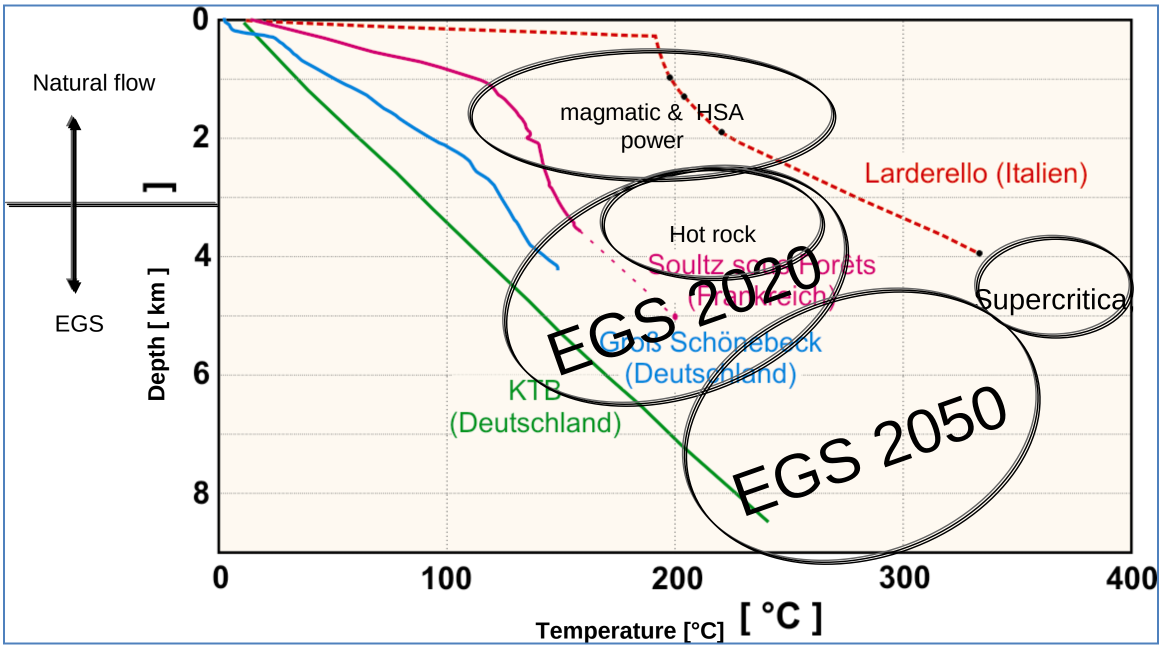


Figure: Relative positioning in depth and temperature gradients of the different play types, and positioning of EGS development (hot rock/EGS correspond to low permeable rock. HSA to hot sedimentary aquifers (which can also be located deeper up to 4km).

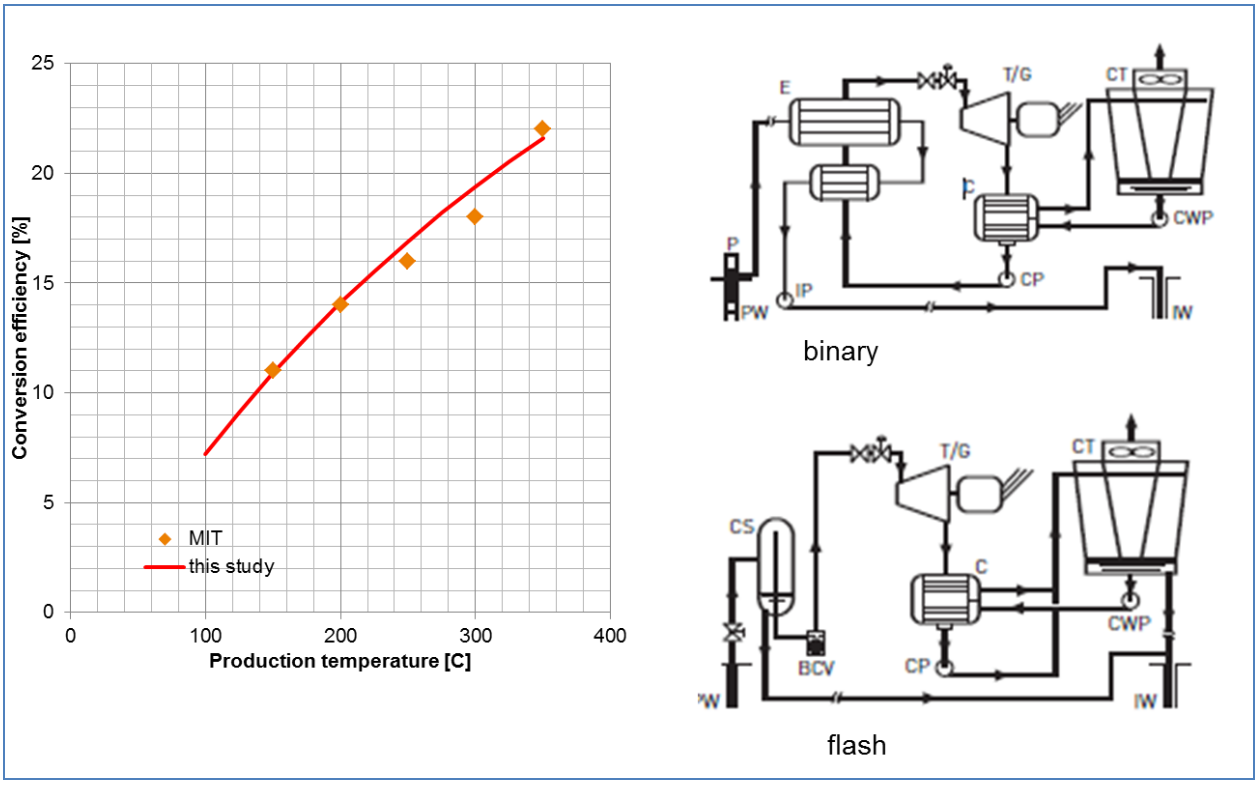


Figure: Practically achieved conversion efficiencies of various geothermal production installations (left), including both binary and flash systems (right) (after Tester et al., 2006). The best fit curve fitting eq.1 for Ts =10C is achieved with η_c =0.6.

The hydrocarbon best practice

Resource classification in the hydrocarbon industry is very well matured and serves as an excellent starting point for geothermal classification and reporting. The publication of Etherington and Ritter (2007; Figure 3.5) forms the latest extension of the Petroleum resource management system accepted by oil and gas industry. Here we summarize the main aspects of the classification scheme which can be useful for geothermal energy. It should be emphasized that geothermal resources in geothermal systems differ from both minerals and petroleum resources by being renewable through recharge, albeit usually at a slower rate than energy is extracted. The rate of this recharge can vary significantly from system to system, and can be stimulated to a varying degree by production.

Prospective Resources are those quantities estimated to be commercially recoverable from yet undiscovered accumulations assuming a discovery is confirmed. While there is always a grey area, a discovery is declared when results of one or more exploratory wells support existence of a significant quantity of potentially moveable hydrocarbons. For geothermal this would agree with confirming a resource through drilling. Discovered quantities should be initially classified as *Contingent Resources*. A portion of these quantities that can be recovered by a *defined commercial project* may then be reclassified as *Reserves*. Commerciality requires that the project form part of an economic venture and the organization claiming commerciality has a firm intention to develop and produce these quantities. Firm intention implies that there is high confidence that any current constraining contingencies will be overcome and that development will be initiated within a reasonable time frame. A reasonable time frame for the initiation of development depends on the specific circumstances and varies according to the scope of the project. In oil and gas industry five years is recommended as a benchmark, however in geothermal development and especially EGS a longer time frame may be applied.

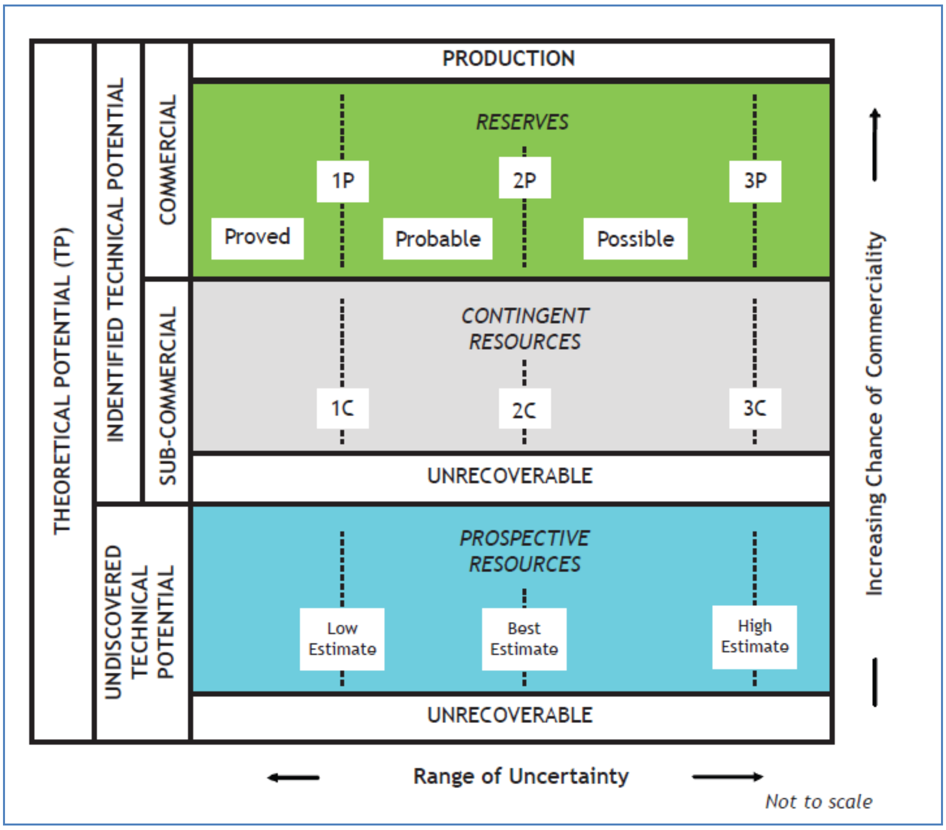


Figure: uncertainty ranges for resource and reserves estimates, and commerciality axis of projects moving them up from prospective resources to contingent resources to reserves (from Etherington and Ritter, 2007). 1,2,3 relates to levels of uncertainty representing low, mid, and high estimates respectively.

2.2 Resource assessment methodology in GEOELEC

Resource assessment in GEOELEC is focused on prospective resources. Reporting can be subdivided in three levels (Figure 3.6):

- *Level 1: Global European prospective resource assessment for producing electricity*
- *Level 2: Prospective undiscovered resource assessment for different play types*
- *Level 3: Contingent (discovered) resources and reserves*

1. Global European prospective resource assessment for producing electricity	European wide assessment (cf. Beardsmore et al., 2010). Determine technical potential for different depth ranges for EGS, key input are base maps of temperature, and rock type to identify theoretical potential. Filter maps with information on natural reserve areas etc. Assume relatively low ultimate recovery in agreement with whole depth column (cf. IPCC, 2011). distinguish relative attractiveness, low, mid, high estimates according to drilling depth required to reach temperature
2. Prospective undiscovered resource assessment for different play types	Identify delimited areas with a particular play type (e.g. Hot Sedimentary Aquifer (HSA), magmatic and low permeability). Include data relevant to exploration of particular play types and exploration outcomes (cf. AGEA-AGEC, 2010) for exploration data relevant to resources assessment
3. Contingent (discovered) resources and reserves	From industry and government reporting obtain information on drilled prospects and producing reserves, play types, development type[1]

Figure: Representation of the various levels of resource categorisation progressing from global (level 1), to prospect based (level 2), to drilling and production (level 3).

[1] However, it can be problematic to gather and disclose publically confidential information from private industry. A minimum period of non-public disclosure applies to the most recent or on-going geothermal projects. For each of these projects authorisation from several private organisations (owner, contractor, sub-contractor) will have to be requested. A regulatory framework on that matter will have to be developed, for instance by the International Geothermal Association, similar to what may already be in force in mining and hydrocarbon explorations.

In depth the resource assessment is limited to 5 or 6.5 km for present developments, but may increase in the future. We therefore propose to develop two timelines, one based on 7 km for 2020 and 2030, one based on 10 km for 2050.

In GEOELEC we perform a global Level 1 assessment. The information gathering for the assessment was accomplished through data workshops and a data request sheet. It was concluded that insufficient data was available for a level 2 or 3. Therefore, an assessment for these levels was not carried out.

The level 1 resource assessment has been performed on a regular 3D hexahedral grid with a horizontal resolution of 20 km and a vertical resolution of 250m. The areas covered by this voxet cover the EU-27 countries including various other countries in Eastern Europe. The area is delineated in the Figure below showing the temperature model.

For each sub volume theoretical to practical potential is calculated, schematically illustrated in the Figure of the schematic workflow to go from theoretical potential to realistic technical potential These calculations are performed for each sub volume of the grid. The calculations are detailed below.

Heat in place (HIP): The heat in place is calculated as the heat energy available in the subsurface. The calculation for a subvolume V:

$$HIP\ [PJ\ ] = V\ * \rho_{rock}\ c_{rock} * (Tx - Ts) * 10^{-15}$$

where

V=volume [m3] of the subsurface subvolume

ρ_{rock} = Density = 2500 kg m-3

C_{rock} = Specific heat = 1000 J kg-1 K-1

Tx = temperature at depth in the subvolume

Ts = temperature at surface

The map of HIP [PJ/km^2] is calculated as the vertical sum of the vertically stacked sub- volumes divided over the surface area of the grid cells in km^2

Theoretical capacity (TC): the *theoretical capacity* [TC] is in agreement with the heat energy in place multiplied by an (electricity) conversion factor which depends on the application:

TC=H *η

Where

$$H = V\ * \rho rock * Cprock * (Tx - Tr) * 10^{-15}\ (\text{in PJ})$$

The heat in place also takes into account the fact that energy cannot be utilized up till the surface temperature. d a return temperature Tr is used, which equals the previously mentioned cut-off production temperature for the application. For electricity production, following Beardsmore et.al. (2010):

To obtain a Theoretical potential map the values in the 3D-grid are vertically summed.

For heat production Tr is significantly lower than for electricity production

Technical potential:

Technical potential denotes the expected recoverable geothermal energy [MW] (e.g. Williams et al., 2008). The technical potential (TP) assumes that the resource will be developed in a period of thirty years. The conversion from *Theoretical capacity* to *Technical potential* is therefore:

$$TP\ [MW/km^2] = 1.057 * TC[PJ/km^2] * R.$$

Where R is the recovery factor which is underlain by various steps, depending also on the delineation of the volume for the TC. For a global assessment, such as performed for chapter 4 on geothermal energy of the IPCC (2011) and Beardsmore et al. (2010), TP considers heat in place of all the sediments and crust beyond a threshold depth in agreement with a cut-off temperature for electricity production systems. In Beardsmore et al., 2010, the ultimate recovery (R) corresponds to:

$R=R_{av}\,R_f\,R_{TD}$,

and includes available land areas, limited technical ultimate recovery from the reservoir based on recovery of heat from a fracture network (R_f) and limitation of operations as an effect of temperature drawdown (R_{TD}). Globally this can result in a recovery of about 1% of the theoretical capacity (IPPC, 2011). The recovery factor of EGS as performed by Beardsmore et al. (2010) does not delineate the reservoir in depth beyond the threshold temperature. For a volumetric delineation which is based on particular play levels leads and prospects (e.g. an aquifer), the recovery factor is generally much higher in the order of 10-50%, whereas the underlying TC involves a significantly lower amount of rock volume.

We propose to use three different levels of TP:

- TPtheory: this is the maximum possible (theoretical) technical potential (R=1.00)
- TPreal: realistic underground Technical Potential according to typical predictive reservoir engineering approaches and empirical practice. This is the equivalent of R_f*R_{TD} in Beardsmore et al., 2012. According to Beardsmore R_f is on average 0.14. R_{TD} is estimated at 90%, resulting in R=0.125. For geothermal aquifers in the Netherlands R is estimated to be 33%
- TPbm: Technical Potential according to Beardsmore et al., 2010 (R=0.01)

Economic technical potential: The economic potential (TPlcoe_p) is calculated from the TPreal, accepting only those subvolumes where the levelized cost of energy (LCOE) is less than a given threshold. The LCOE depend on the application (*power, power and co-heat*). The economics takes as input the expected flow rate. In TPlcoe_p, p denotes the cumulative probability (0..100%) of exceeding the flow rate and temperatures used. The economic evaluation considers the achievable flow-rate as major technical uncertainty

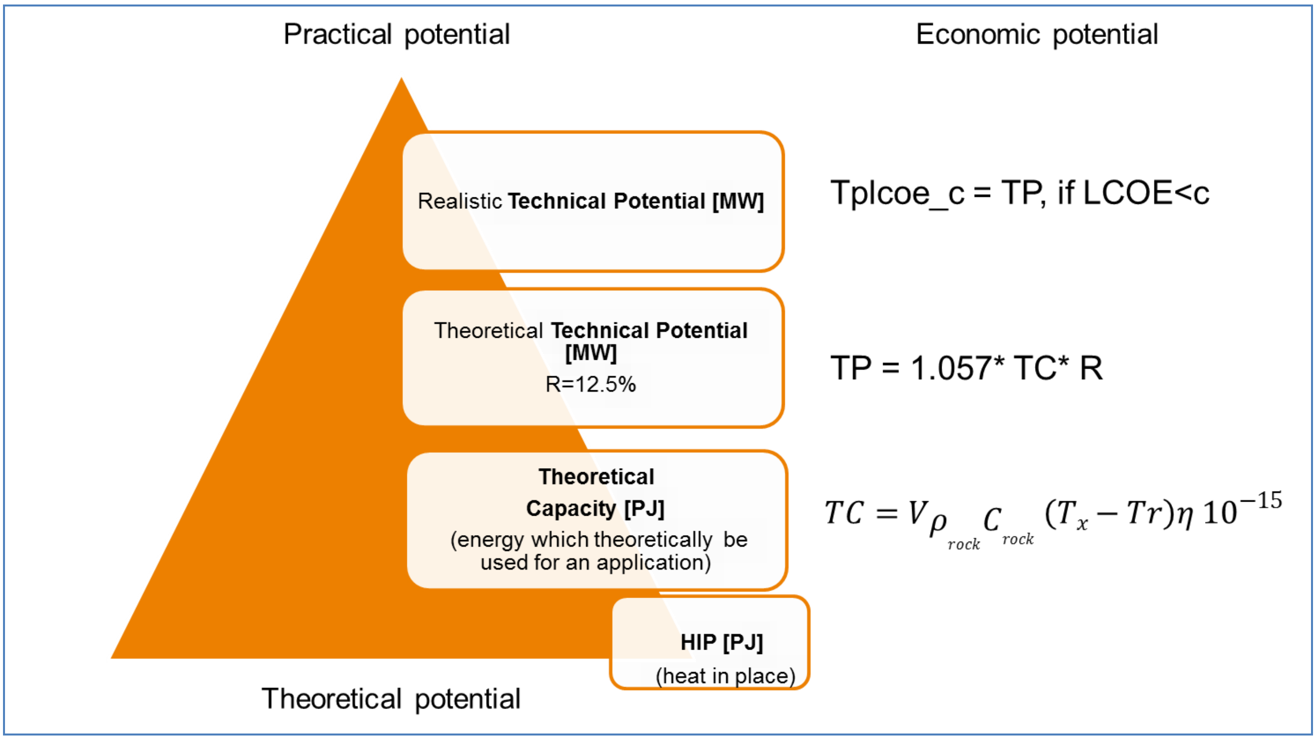


Figure: Schematic workflow to go from theoretical potential to realistic technical potential.

For the maps the sub volume results are vertically summed, and subsequently divided over the area of the grid cell in km^2. The following maps have been calculated

Map	Name	Unit
HIP	Heat in place	PJ/km^2
TC	Theoretical capacity	PJ/km^2
TPtheory	Theoretical Technical Potential (R=1)	MW/km^2
TPbm	Technical Potential according to Beardsmore et al., 2010 (R=0.01)	MW/km^2
TPreal	Technical Potential (R=0.125)	MW/km^2

TPlcoe_c	Realistic Technical Potential (LCOE<c) adopting TPreal	MW/km^2

Table: type of potential maps in the information system

Map	Name	Unit
LCOE	Minimum Levelized Cost of Energy in a vertical stack of the 3D grid	€/MWh
LCOEDEPTH	Depth of the Minimum Levelized Cost of Energy in a vertical stack of the 3D grid	km

Table: Additional maps based on the 3D grid calculations

For the country outlooks it is assumed that 25% of the economic (realistic technical) potential in MWe can be installed on a country basis, due to restrictions in land use. For the conversion from installed capacity to TWh a load factor of 90% is adopted.

LCOE analysis and sensitivities

For the economic analysis of the levelised cost of energy (LCoE) a cash flow calculation is performed. A dominant cost item in the analysis is the cost of drilling and stimulation. For the costs of drilling we assume three different scenarios for the 2020, 2030 and 2050 timelines, based on an exponential and linear well cost model. More detailed information well, stimulation and plant costs and performance aspects is given in section 3.3

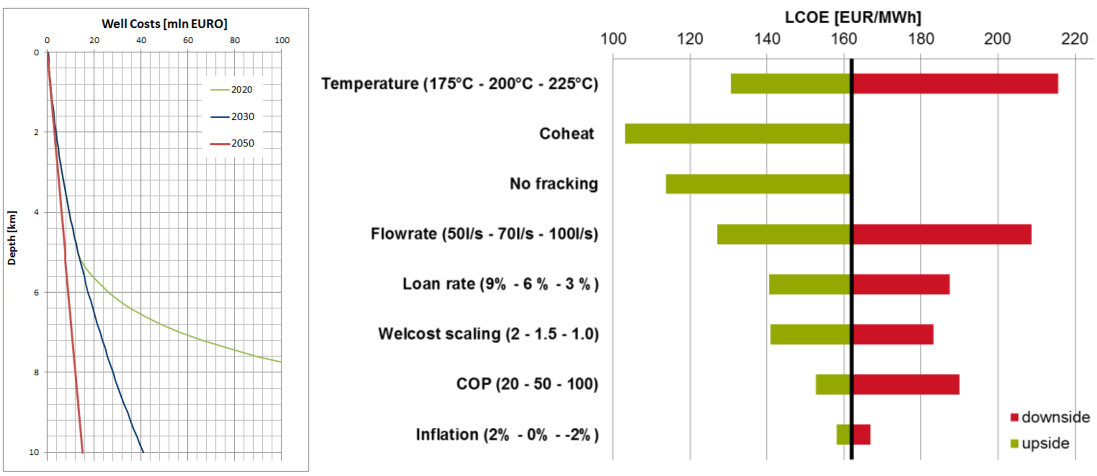


Figure. well costs (for EGS 2 wells have been assumed) and sensitivities of predicted LCOE to input parameters for the 2030 scenario at a potential EGS location at 5 km depth with forecasted resource temperature of 200°C.

Uncertainty and CHP

Within the 2030 scenario we considered the effect of uncertainty in flow rate and effects of combined heat and power (CHP) on the resource base.

For uncertainty in flow rate we assumed a deviation of +-30% of the default flow rate and its effects. For CHP it has been assumed that heat sales are 9 EUR/GJ and account for the thermal power which can be generated from Tr to a reinjection temperature of 35C. CHP can result in a reduction of the LCoE of about 50 EUR/MWh, whereas increase in flow rates can decrease LCoE typically by 10-50 EUR/MWh.

3. Geothermal power economic potential in Europe

To give a best representation of the prospects for geothermal electricity, it is essential to choose the proper scenarios. Adjusting the scenarios severely alter the outcome of the prospects. The most influential parameter for an economical prospect is the chosen cut-off value, e.g. feed-in tariff, price of electricity - including premiums. With a very high cut-off value, eventually all targets can be developed economically.

To get a best representation, the following scenarios are chosen. For the years 2020, 2030 and 2050 the cut-off value decreases. In other words, the feed-in tariffs decrease. For the near future (2020) we assume a cut-off of 200 euro per MWh, which corresponds to 20 eurocents per kilowatt-hour. Ten years further in the future, we assume feed-in tariffs or premiums are less necessary in comparison to 2020. Here a cut-off of 150 euro per MWh is chosen. Towards 2050 this decreases further down to 100 euro per MWh.

These chosen cut-off values only represent the economic boundaries for the prospects. But also on the technical side of the scenarios developments are defined which favour the prospects. The assumptions are shown in the Table below. The maximum depth range increases, due to assumed improved drilling techniques, from 7 kilometres depth to 10 kilometres depth in 2050. Also the flow rates increase due to better stimulation techniques from 50 L/s to 100 L/s in 2050. As the effect of stimulation increases in flow rate, the costs for stimulation remain the same: EUR 10mln. To reach the maximum drilling depths, improvements in drilling techniques lead to a different, more beneficial well cost model. Where the well cost model increases exponential with depth in 2020, it is assumed to be less depth dependent in 2050, resulting in a more linear relation. The efficiency in both the system and in conversion increases. The coefficient of performance increases from 30 in 2020 to 50 in 2030 and 1000 in 2050. The relative Carnot efficiency increases from 60% in the near future to 70% in 2050. In addition the use of heat to convert to electricity is more efficient and the combined heat and power outlet remains equal.

Parameter	Unit	2020	2030	2050
Maximum Depth	km	7	7	10
Flow Rate	L/s	50	70	100
COP	-	30	50	1000
Well Cost Model	-	Wellcost Scaling 1.5 + Exponential	Wellcost Scaling 1.5	Linear 1500€/m
Stimulation Costs	Mln €	10	10	10
Relative Carnot Efficiency	-	0.6	0.6	0.7
Tinc for Tr (Tr=Tsurface + Tinc)	^{0}C	80	80	50
CHP outlet	^{0}C	35	35	35

Table: Assumptions for the prospective study (COP = Coefficient of Performance | CHP = Combined Heat and Power)

The cut-off values, e.g. feed-in tariffs, may change per country and be adapted to national circumstances and according to the maturity of the technology and/or the market.. Therefore not only one single cut-off value is represented. Also a Table displaying a range of cut-off values, stacking the gained potential with increasing cut-off values:

SCENARIO	Cut-off range	Steps
2020	Less than 100 EUR/MWh to a maximum of 300 EUR/MWh	100 – 150 – 200 – 300
2030 & 2050	Less than 50 EUR/MWh to a maximum of 200 EUR/MWh	50 – 100 – 150 – 200

Table: Overview of cut-off values for the defined scenarios

The cut-offs apply for power-only, and do not include CHP. Finally the economic geothermal potential for electricity production is presented as maps of the LCoE and at which these cut-off values can be reached. See below an overview of all available maps and scenarios:

Scenario	2020	2030	2050
Maps	LCOE	LCOE	LCOE
	LCOEDEPTH	LCOEDEPTH	LCOEDEPTH
	TP for cut-off lower than 300EUR/MWh	TP for cut-off lower than 200EUR/MWh	TP for cut-off lower than 150EUR/MWh
	TP for cut-off lower than 200EUR/MWh	TP for cut-off lower than 100EUR/MWh	TP for cut-off lower than 100EUR/MWh
	TP for cut-off lower than 100EUR/MWh	TP for cut-off lower than 50EUR/MWh	TP for cut-off lower than 50EUR/MWh

Table: Overview of available maps in the report. For all maps produced in this project, go to www.thermogis.nl/geoelec (TP = Technical Potential)

Country outlooks

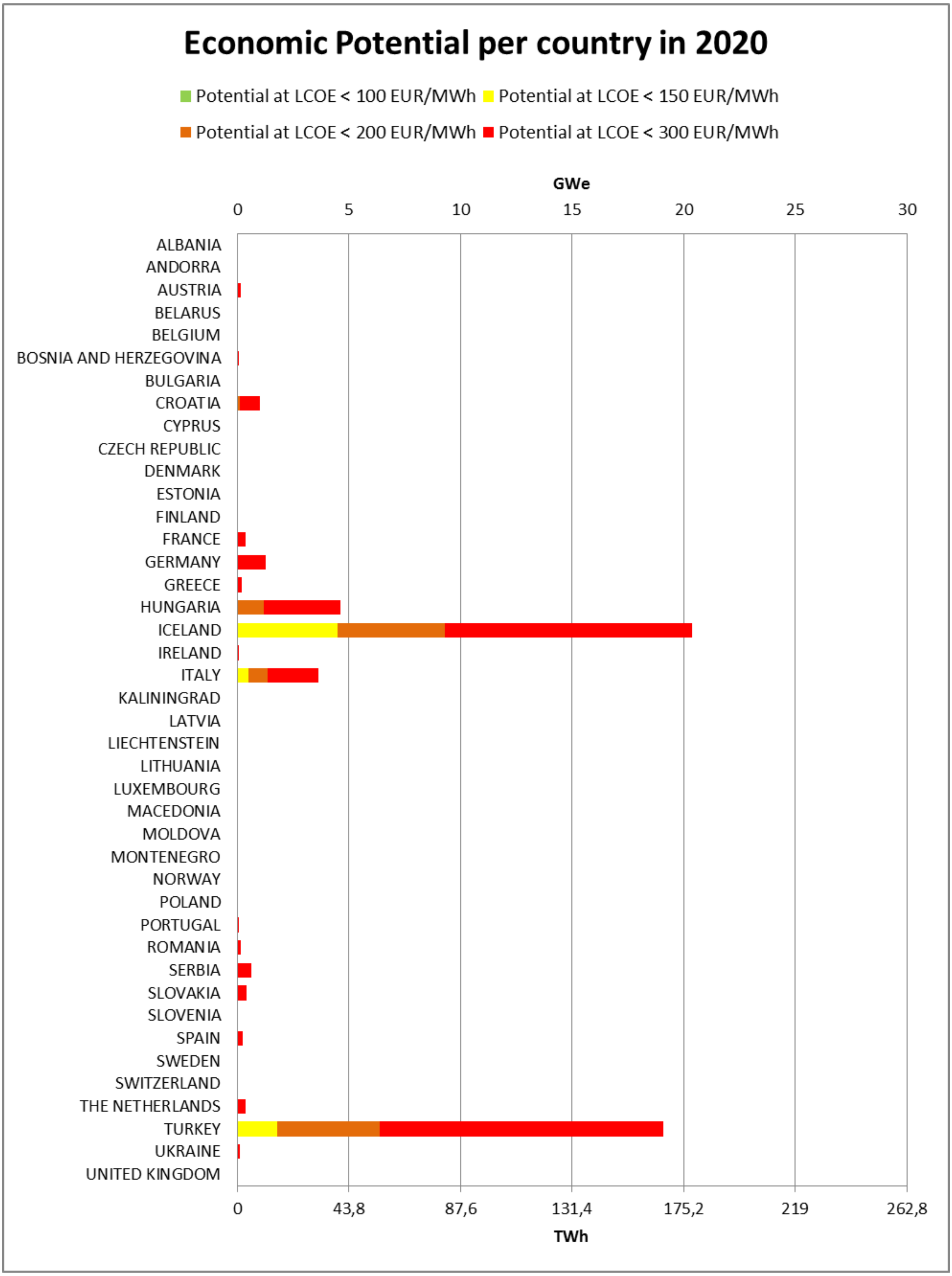
At this point the scenarios are described and the maps of Europe presented. The question which logically may arise is what that means per country. Hereby we present the outlook per country, both in a chart displaying the potential per country for 2020, 2030 and 2050.

The Table below shows the potential per country in TWh for the 2020, 2030 and 2050 scenarios. This is the economic potential based on the above mentioned assumptions and no application of co-heat (for the effects of the application of co-heat, see next chapter). For the chosen scenarios we assume a LCoE of less than 200 EUR/MWh for 2020, a LCOE of less than 150 EUR/MWh for the 2030 scenario and for 2050 a LCoE of less than 100 EUR/MWh.

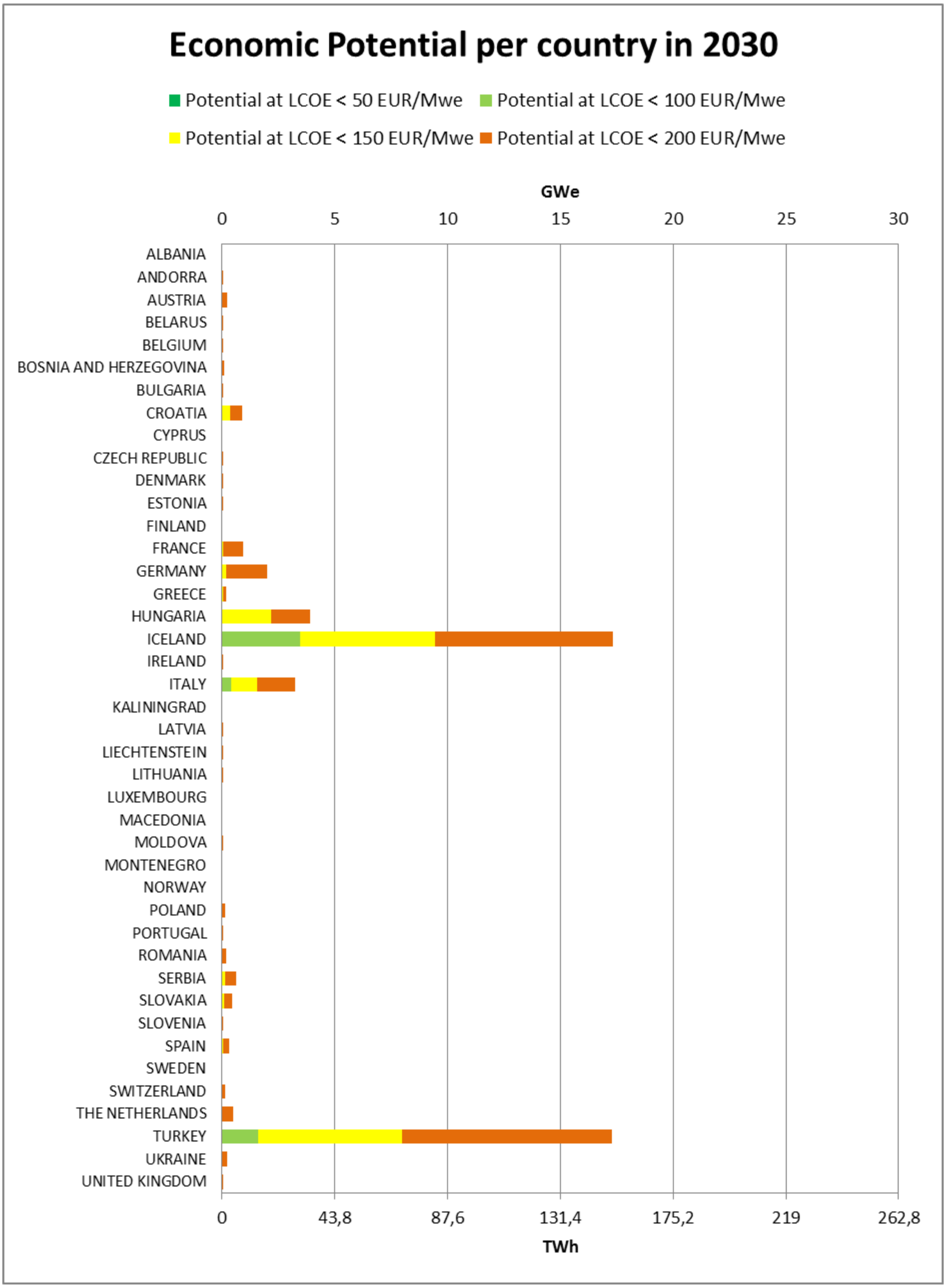
As the current and projected financial support may differ per country, below the economic geothermal potential is presented in stacked potential of all assessed cut-off values. The ranges are shown in Table. **A very low cut-off value results in a minimal economic potential, whereas very high cut-off values make more geothermal resources within economic reach.**

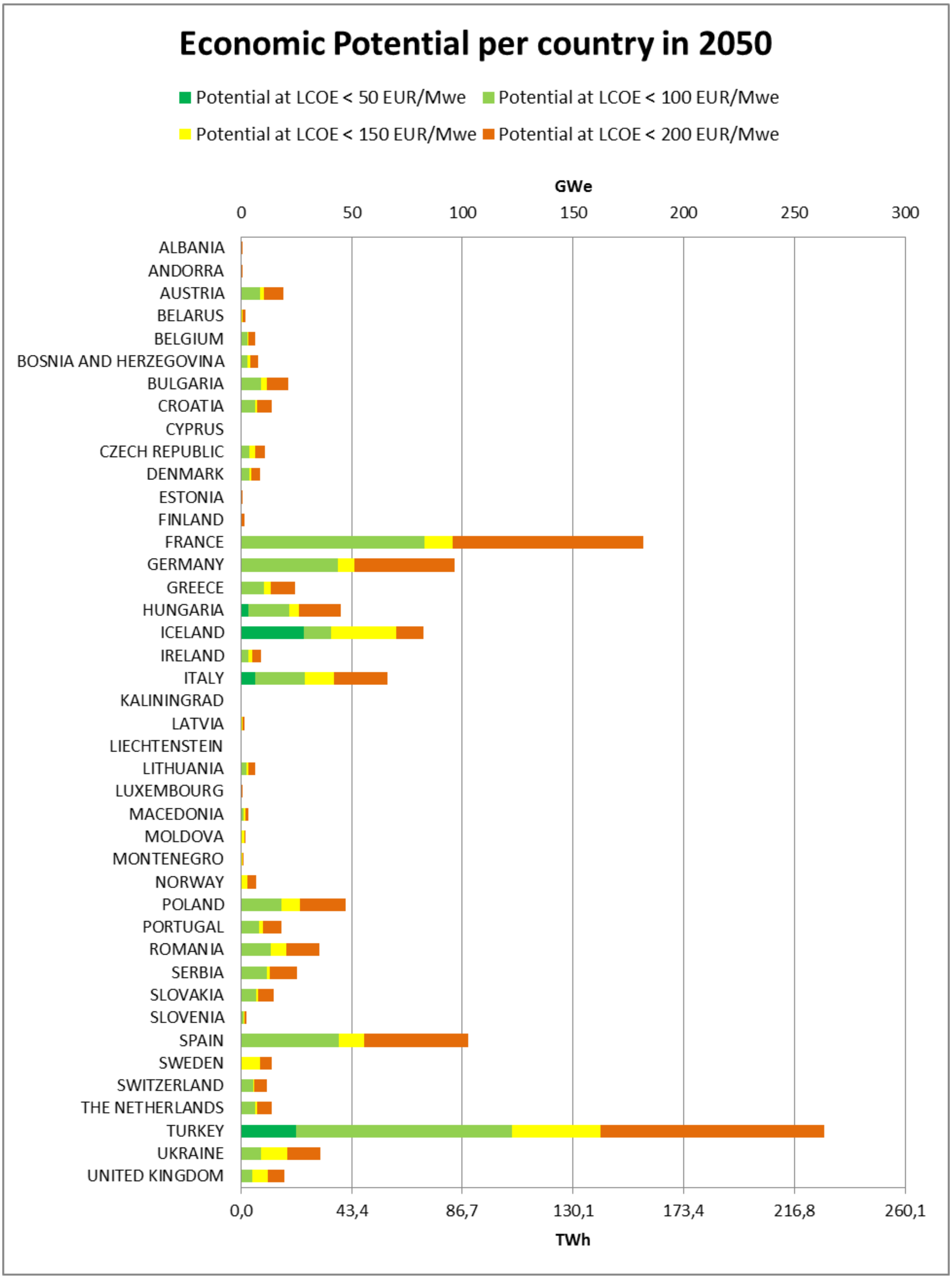
Country	Economic Potential (in TWh)		
	2020	2030	2050
ALBANIA	0	0	0
ANDORRA	0	0	1
AUSTRIA	0	0	67
BELARUS	0	0	2
BELGIUM	0	0	22
BOSNIA AND HERZEGOVINA	0	0	25
BULGARIA	0	0	72
CROATIA	1	3	50
CYPRUS	0	0	0
CZECH REPUBLIC	0	0	31
DENMARK	0	0	29
ESTONIA	0	0	2
FINLAND	0	0	0
FRANCE	0	0	653
GERMANY	0	1	346
GREECE	0	0	81
HUNGARIA	9	17	174
ICELAND	73	74	322
IRELAND	0	0	27
ITALY	11	12	226
KALININGRAD	0	0	0
LATVIA	0	0	3
LIECHTENSTEIN	0	0	0
LITHUANIA	0	0	19
LUXEMBOURG	0	0	3
MACEDONIA	0	0	10
MOLDOVA	0	0	2
MONTENEGRO	0	0	2
NORWAY	0	0	0
POLAND	0	0	144
PORTUGAL	0	0	63
ROMANIA	0	0	105
SERBIA	0	1	92
SLOVAKIA	0	1	55
SLOVENIA	0	0	8
SPAIN	0	1	349
SWEDEN	0	0	1
SWITZERLAND	0	0	43
THE NETHERLANDS	0	0	52
TURKEY	50	62	966
UKRAINE	0	0	71
UNITED KINGDOM	0	0	42

Table: Economic Potential per country (2020 = LCOE < 200 EUR/MWh; 2030 = LCOE < 150 EUR/MWh; 2050 = LCOE < 100 EUR/MWh)



Economic Potential per country in 2020
Potential at LCOE < 100 EUR/MWh
Potential at LCOE < 150 EUR/MWh
Potential at LCOE < 200 EUR/MWh
Potential at LCOE < 300 EUR/MWh
GWe
0
5
10
15
20
25
30
ALBANIA
ANDORRA
AUSTRIA
BELARUS
BELGIUM
BOSNIA AND HERZEGOVINA
BULGARIA
CROATIA
CYPRUS
CZECH REPUBLIC
DENMARK
ESTONIA
FINLAND
FRANCE
GERMANY
GREECE
HUNGARIA
ICELAND
IRELAND
ITALY
KALININGRAD
LATVIA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MACEDONIA
MOLDOVA
MONTENEGRO
NORWAY
POLAND
PORTUGAL
ROMANIA
SERBIA
SLOVAKIA
SLOVENIA
SPAIN
SWEDEN
SWITZERLAND
THE NETHERLANDS
TURKEY
UKRAINE
UNITED KINGDOM
0
43,8
87,6
131,4
175,2
219
262,8
TWh


Economic Potential per country in 2030
Potential at LCOE < 50 EUR/Mwe
Potential at LCOE < 100 EUR/Mwe
Potential at LCOE < 150 EUR/Mwe
Potential at LCOE < 200 EUR/Mwe
GWe
0
5
10
15
20
25
30
ALBANIA
ANDORRA
AUSTRIA
BELARUS
BELGIUM
BOSNIA AND HERZEGOVINA
BULGARIA
CROATIA
CYPRUS
CZECH REPUBLIC
DENMARK
ESTONIA
FINLAND
FRANCE
GERMANY
GREECE
HUNGARIA
ICELAND
IRELAND
ITALY
KALININGRAD
LATVIA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MACEDONIA
MOLDOVA
MONTENEGRO
NORWAY
POLAND
PORTUGAL
ROMANIA
SERBIA
SLOVAKIA
SLOVENIA
SPAIN
SWEDEN
SWITZERLAND
THE NETHERLANDS
TURKEY
UKRAINE
UNITED KINGDOM
0
43,8
87,6
131,4
175,2
219
262,8
TWh


Economic Potential per country in 2050
Potential at LCOE < 50 EUR/Mwe
Potential at LCOE < 100 EUR/Mwe
Potential at LCOE < 150 EUR/Mwe
Potential at LCOE < 200 EUR/Mwe
GWe
0
50
100
150
200
250
300
ALBANIA
ANDORRA
AUSTRIA
BELARUS
BELGIUM
BOSNIA AND HERZEGOVINA
BULGARIA
CROATIA
CYPRUS
CZECH REPUBLIC
DENMARK
ESTONIA
FINLAND
FRANCE
GERMANY
GREECE
HUNGARIA
ICELAND
IRELAND
ITALY
KALININGRAD
LATVIA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MACEDONIA
MOLDOVA
MONTENEGRO
NORWAY
POLAND
PORTUGAL
ROMANIA
SERBIA
SLOVAKIA
SLOVENIA
SPAIN
SWEDEN
SWITZERLAND
THE NETHERLANDS
TURKEY
UKRAINE
UNITED KINGDOM
0,0
43,4
86,7
130,1
173,4
216,8
260,1
TWh

Combined Heat & Power (CHP)

In the previous chapter you can find a sensitivity diagram showing the effects of different variables on the LCoE. The majority of the parameters have both a positive and negative effect; e.g. the required temperature can be both lower and higher. A higher required temperature means a well to greater depths, hence higher drilling costs resulting in a higher LCoE. There are two parameters which indisputable benefit the LCoE: when no stimulation is needed or when co-heat is applied.

As an example we'll look at the application of co-heat. A cascading system of first electricity generation using the high temperature geothermal source, followed by the use of lower temperature residual heat for the use of direct heat (spatial heating, greenhouses, etc.).

The sensitivity diagram shows in a best case scenario a lowering of the LCoE by 50 euro. In the diagram the LCoE drops from 160 EUR/MWh to approximately 110 EUR/MWh. This same principal can be applied to the country outlooks and the maps. Assuming a co-heat scenario may increase the potential in each country from the < 150 EUR/MWh scenario to a < 100 EUR/MWh scenario.

The exercise of resource assessment produced maps of the geographical distribution and extent of the potential, which are shown in the next pages. For a full overview of all produced maps, go to www.thermogis.nl/geoelec.

The maps are sorted by scenario (2020 to 2050) and display the technical potential for a certain LCoE. The used cut-off values are in line with the values mentioned above. A full set of maps depicting the distribution of the Levelised costs of Energy, followed by the corresponding minimum depths at which the LCoE can be obtained are available in Annex II.

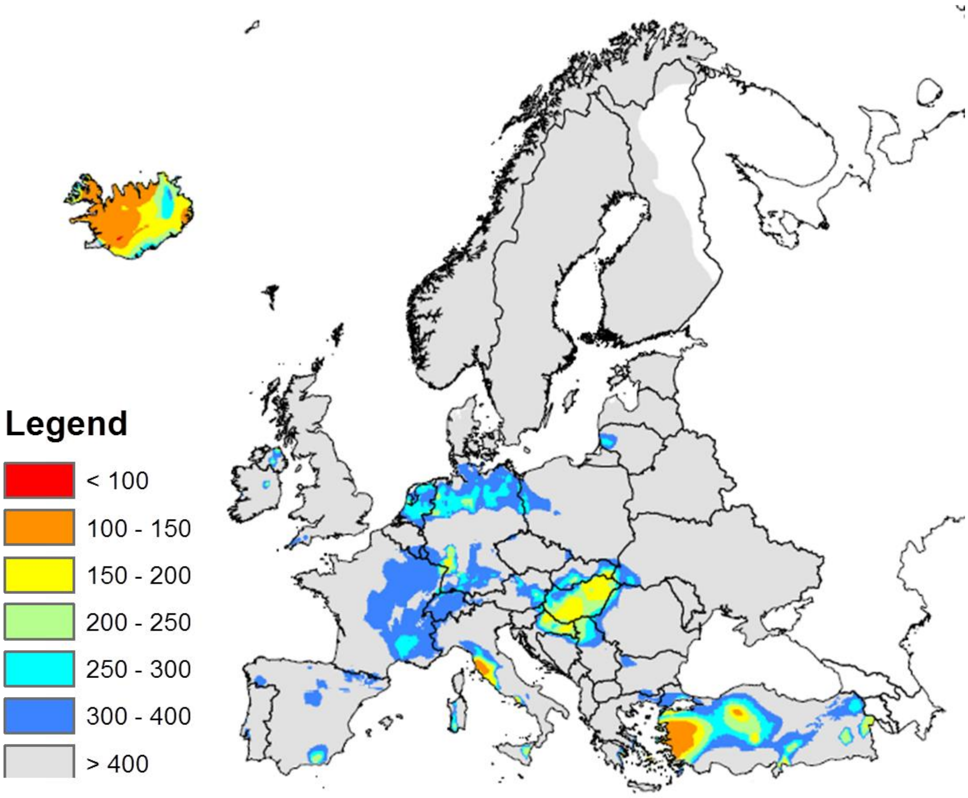


Figure: Minimum levelized costs of Energy in 2020 (in EUR/MWh)

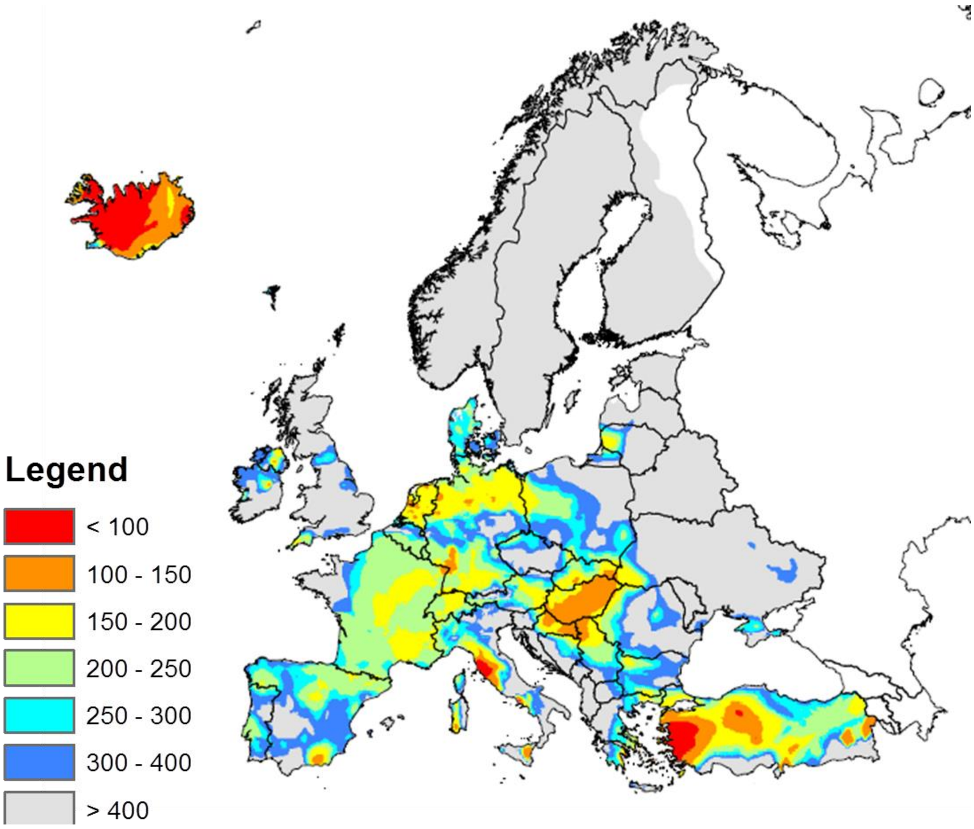


Figure: Minimum levelized costs of Energy in 2030 (in EUR/MWh)

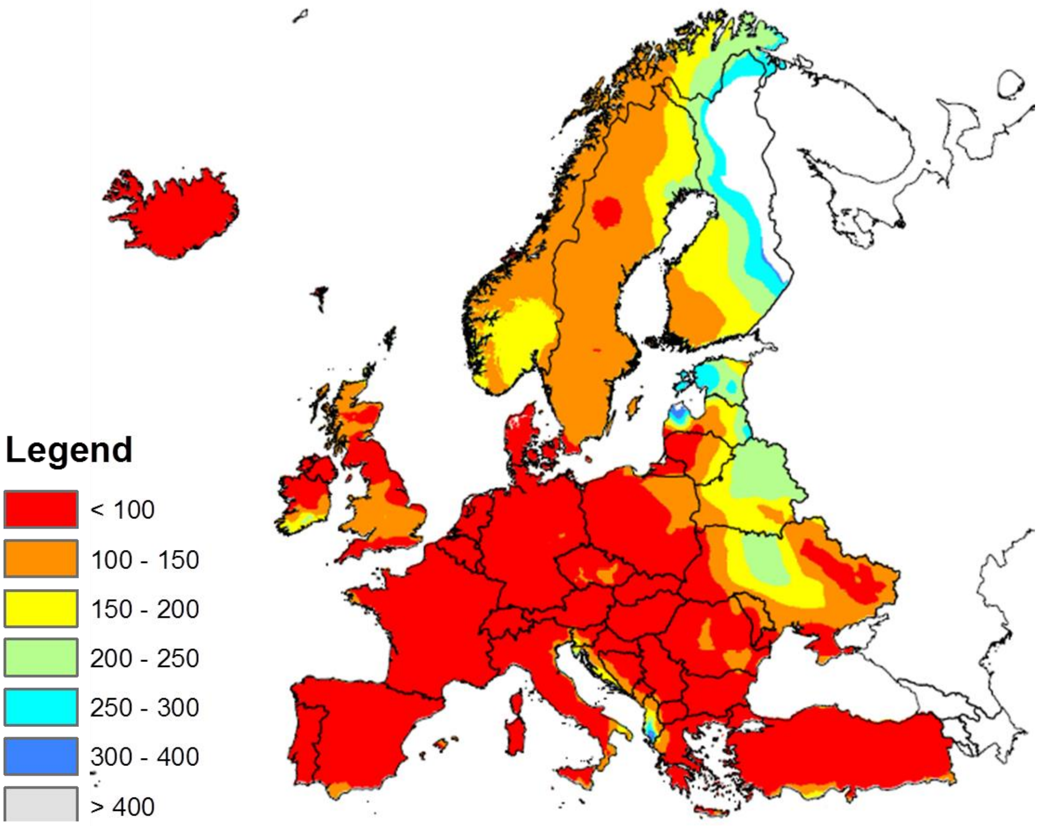


Figure: Minimum levelized costs of Energy in 2050 (in EUR/MWh)

4. Recommendations for policy-makers

In order to realise and reap the all the benefits for the EU as a whole of the geothermal electricity potential stemming from this study, the GEOELEC project puts forward the following recommendations for policy-makers:

- **Create conditions to increase awareness about the advantages of this technology and its potential. National Committees on Geothermal promoting the technology to decision-makers and engaging the civil society to favour social acceptance should be established.**

The potential of geothermal energy is recognised by some EU Member States in their National Renewable Energy Action Plans (NREAPs). However, the actual potential is significantly larger. In order to increase awareness, GEOELEC has assessed and presented for the first time the economic potential in Europe in 2020, 2030 and 2050. The figures are quite impressive, showing the large potential of geothermal and the important role it can play in the future electricity mix.

One objective of the GEOELEC project is to promote across the EU the creation of National Geothermal Committees. Such committee should be established in each EU-28 Member States with the objective to increase awareness about geothermal and to ensure public acceptance of the geothermal projects.

This initiative is coming from France where such a Committee has already been established in July 2010: The Energy Ministry launched a 'Comité National de la géothermie' to propose actions and recommendations for a geothermal development in France. It is composed by 35 members from 5 different sectors: State level, Local authorities, NGOs, Employers, Workers. The first Results of the Comité National de la géothermie in France can be presented through 3 key actions:

- Simplifying administrative procedure and quality
- Training professionals
- Disseminating information

- **Contribute to the economic competitiveness of Europe by providing affordable electricity. In order to progress along the learning curve and deploy at large-scale a reliable renewable technology, a European EGS flagship programme should be launched, including new demonstration plants and test laboratories: it should also look at new technologies, methods and concepts.**

EGS is a technology for accessing the heat in hot but impermeable basement rock. Once fully developed it will provide a major increase in the geothermal resource base, both for heat and electric power. In spite of its potential and although the basic concepts have been developed already in the 1980s EGS has not matured yet into a ready-to-implement technology.

An EGS Flagship program in the EU should be launched for making this technology competitive at the horizon 2020. Ultimately, this will establish EGS as a technology applicable almost everywhere for both heat and power production.

At each stage of EGS development, proven methodologies can be applied and bottlenecks identified. From this state-of-the-art assessment, priorities encompassing five main areas have been defined for medium to long term research. The expected outcome will be geothermal energy in a form that can be widely deployed and competitively priced, underpinned with reduced capital, operational and maintenance costs. Swift progress (and continuous improvement) will be pooled with coordinated international R&D efforts, with a view to successful demonstration and implementation.

- Establish network of complementary 5-10 European EGS test laboratories.
- Develop Demonstration sites in different geological settings and upscale size of the power plants
- Launch Training and education programs for new geothermal professionals specialized in EGS.
- Ensure Public acceptance on microseismicity, stimulation, environmental impact, emissions
- Towards grid flexibility: Flexible and base load electricity production from EGS plants, with test on dispatchability, for designing regional flexible electricity system.

• **Establish the economic and financial conditions for geothermal development: a European Geothermal Risk Insurance Fund (EGRIF) is an innovative option tailored to the specificities of geothermal to mitigate the cost of the geological risk and is a complementary tool to operational support, still needed to compensate for the long-standing lack of a level-playing field.**

Financing a geothermal project includes two crucial elements in the initial phase of the project development: a high capital investment for drilling wells which can take up to 70% of the total project costs, and an insurance scheme to cover the geological risks.

As pre-drill assessment of geothermal performance is subject to major uncertainty and EGS (Enhanced Geothermal System) is in an embryonic development phase, the risk profile is high compared to alternative sources of renewable energy. In order to face these challenges the following financial incentives are required to facilitate growth of geothermal energy in Europe:

- Support schemes are crucial tools of public policy for geothermal to compensate for market failures and to allow the technology to progress along its learning curve;
- Innovative financing mechanisms should be adapted to the specificities of geothermal technologies and according to the level of maturity of markets and technologies;
- A European Geothermal Risk Insurance Fund (EGRIF) is seen as an appealing public support measure for overcoming the geological risk;
- While designing a support scheme, policy-makers should seek a holistic approach, which exceeds the LCoE and includes system costs and all externalities. As an alternative, there is the chance to offer a bonus to geothermal energy for the benefits it provides to the overall electricity system, balancing the grid.

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Annex I: GEOELEC Maps on Geothermal electricity potential

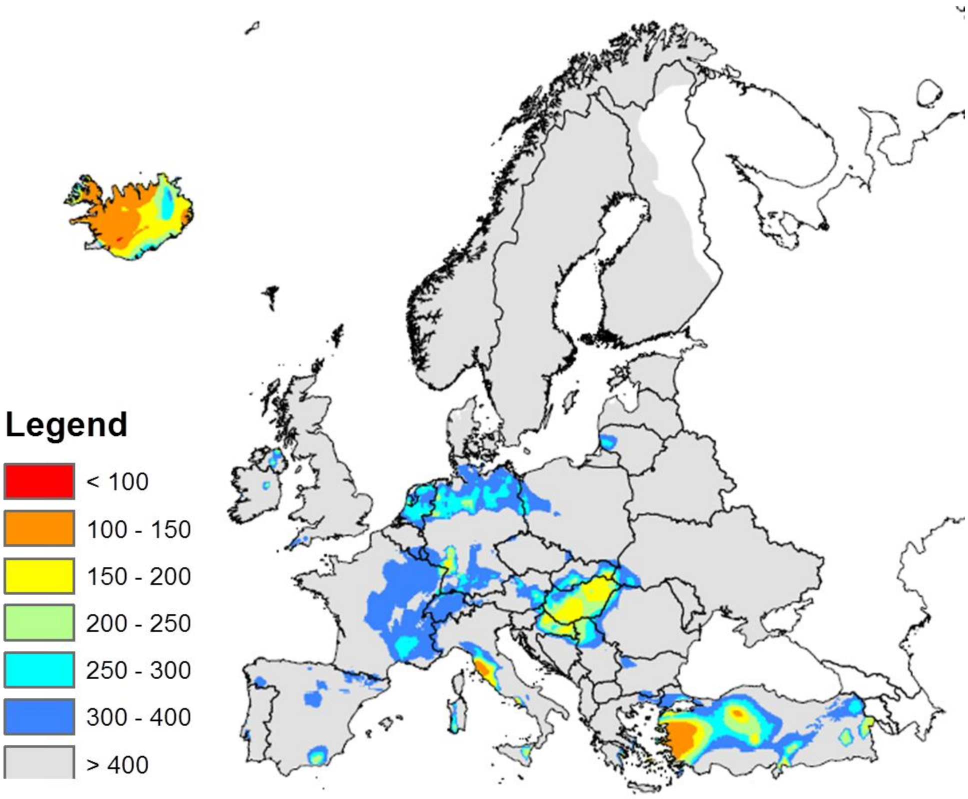

Figure: Minimum levelized costs of Energy in 2020 (in EUR/MWh)

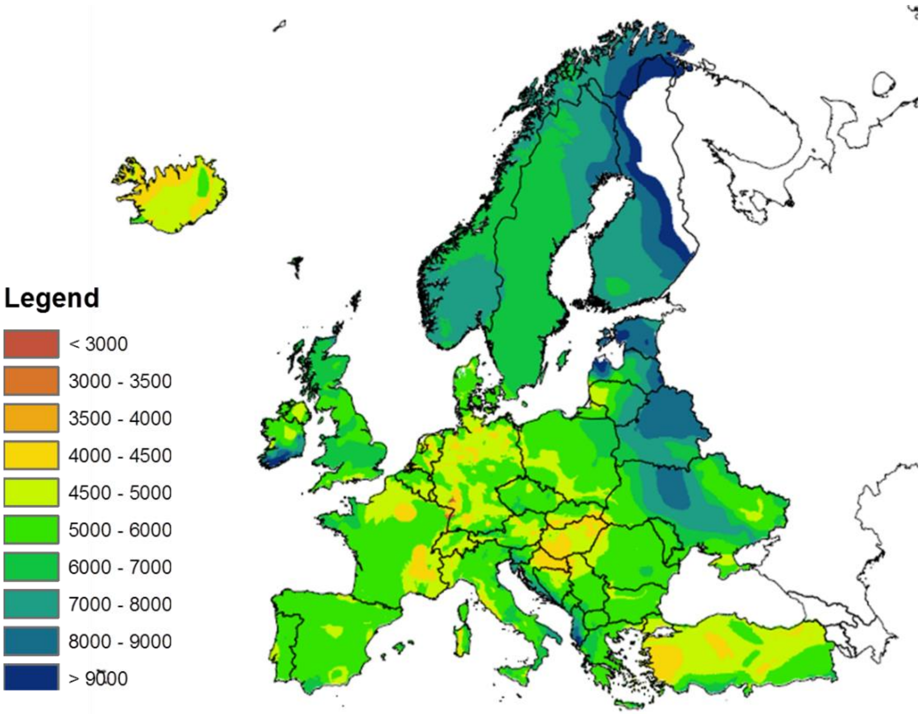

Figure: Depth at which the Minimum levelized costs of Energy is found in 2020 (in m)

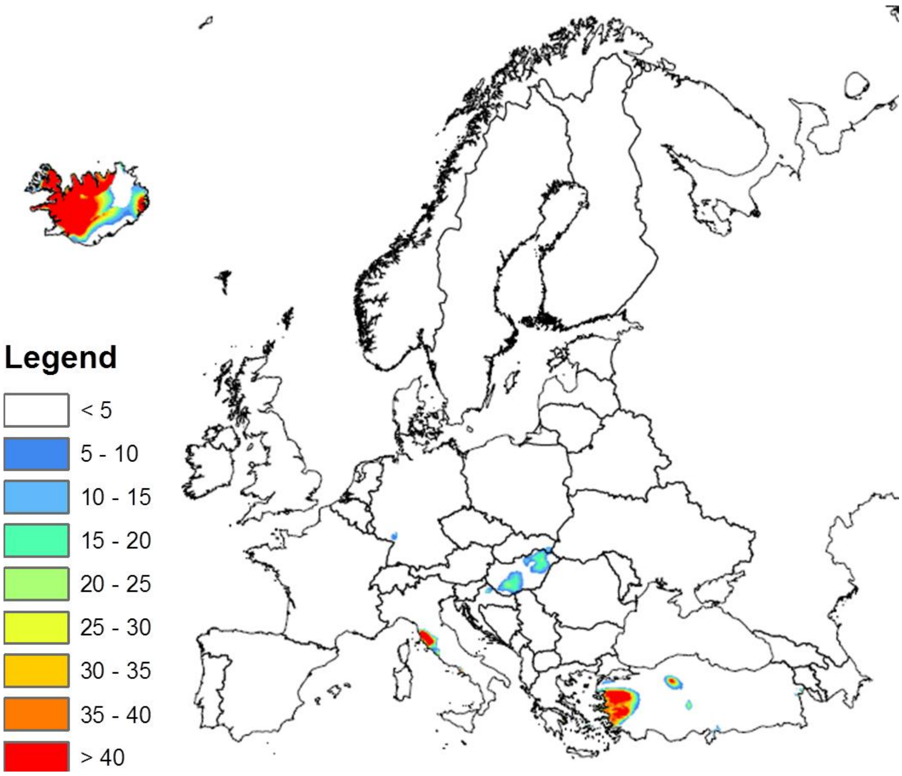

Figure: Technical Potential for a Levelized Cost of Energy in 2020 < 200 EUR/MWh (in MW/km2)

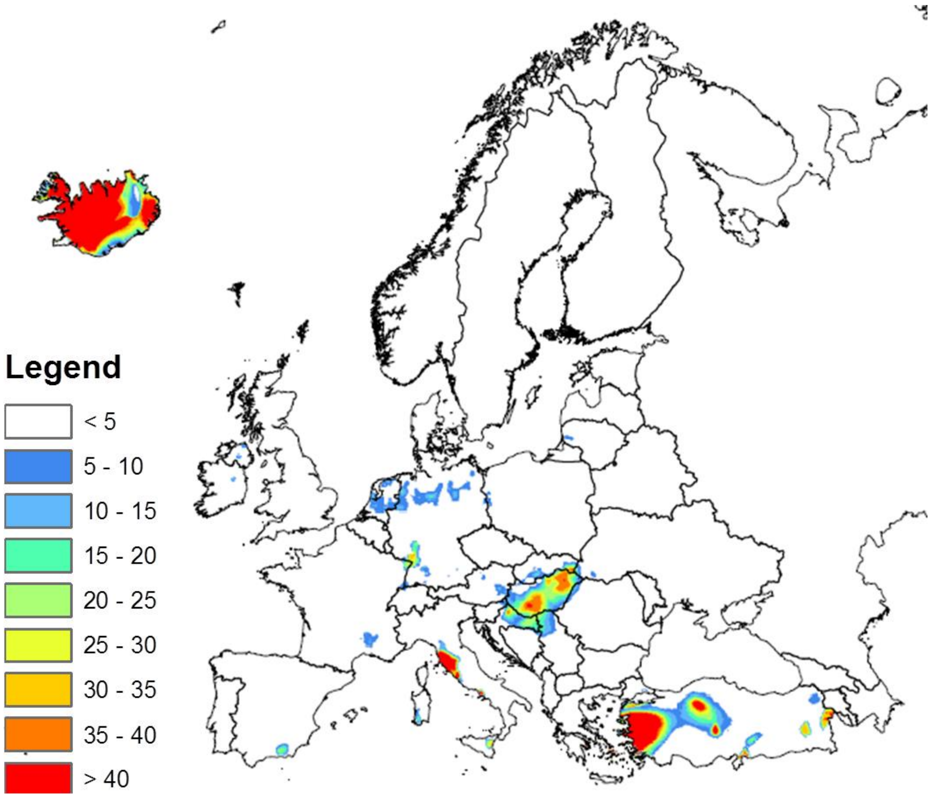

Figure: Technical Potential for a Levelized Cost of Energy in 2020 < 300 EUR/MWh (in MW/km2)

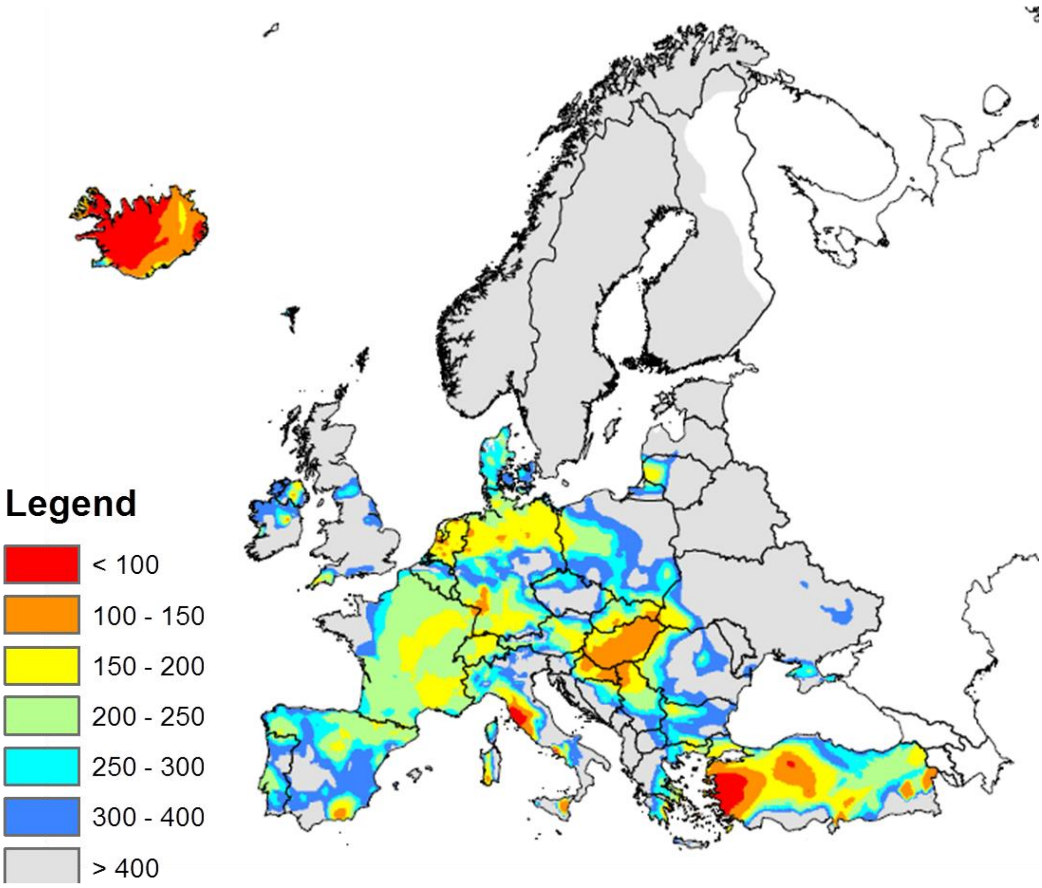

Figure: Minimum levelized costs of Energy in 2030 (in EUR/MWh)

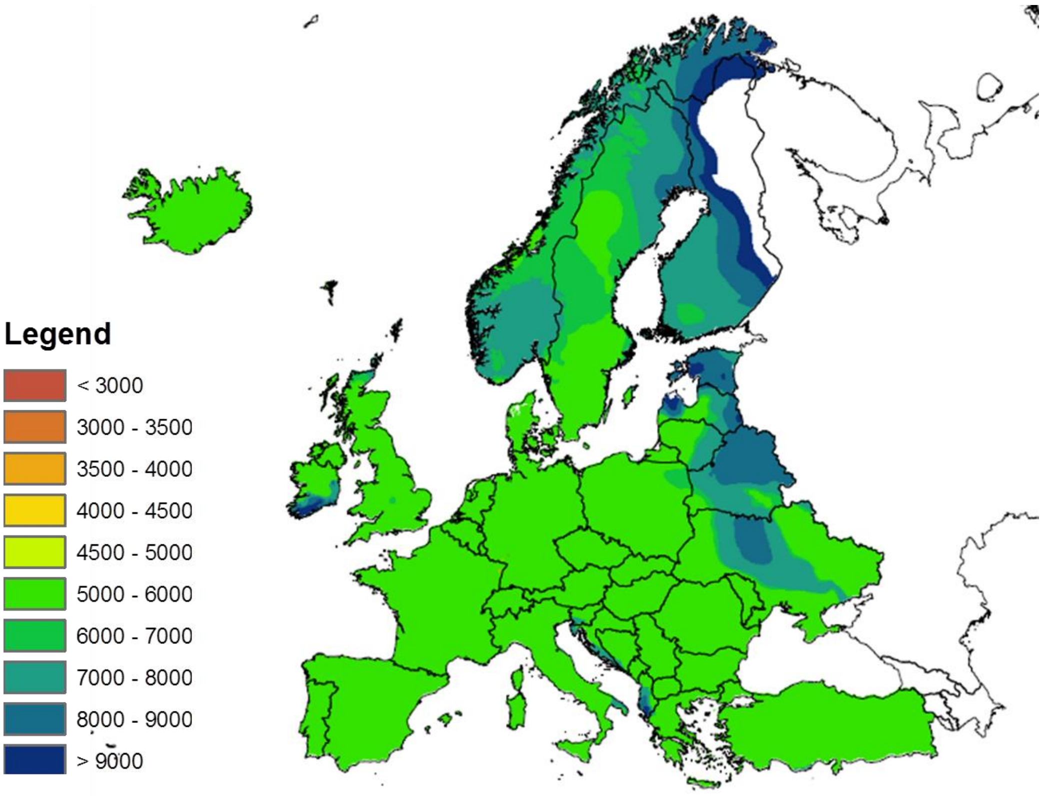

Figure: Depth at which the Minimum levelized costs of Energy is found in 2030 (in m)

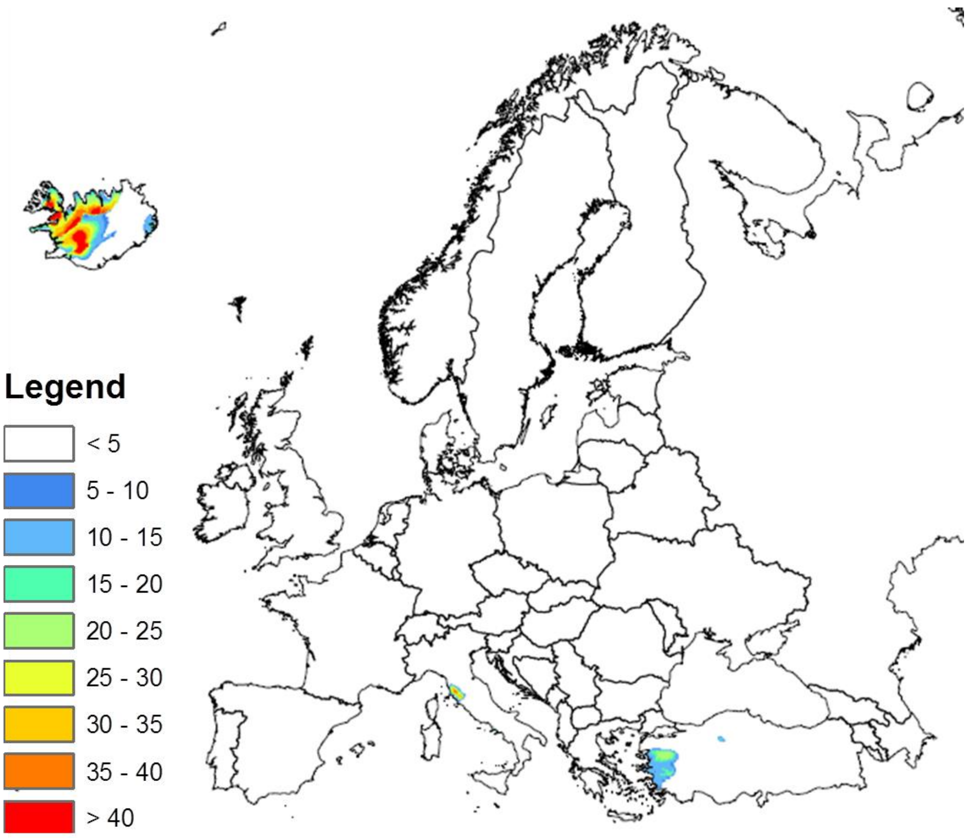

Figure: Technical Potential for a Levelized Cost of Energy in 2030 < 100 EUR/MWh (in MW/km2)

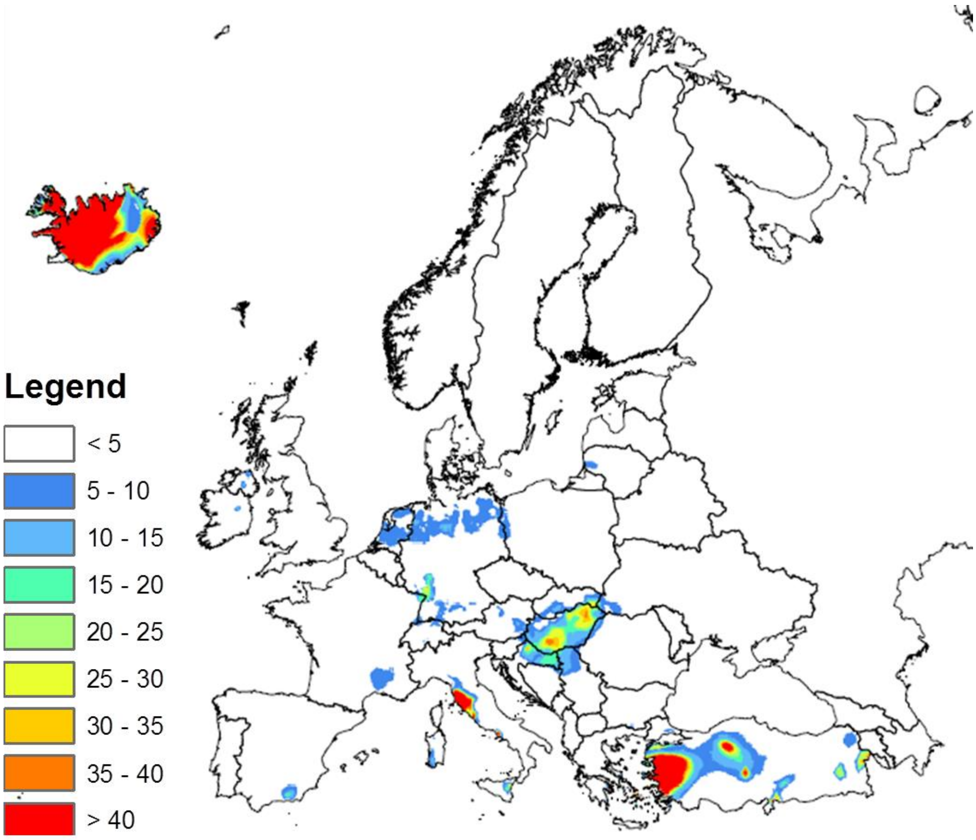

Figure: Technical Potential for a Levelized Cost of Energy in 2030 < 200 EUR/MWh (in MW/km2)

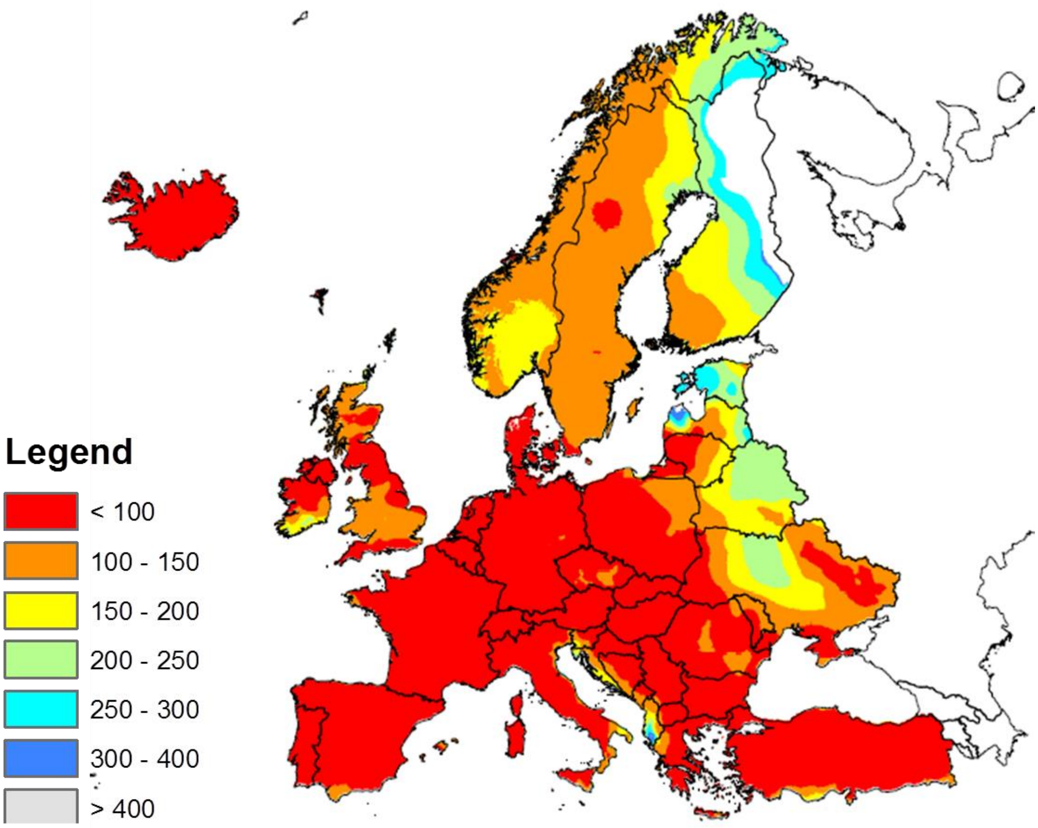

Figure: Minimum levelized costs of Energy in 2050 (in EUR/MWh)

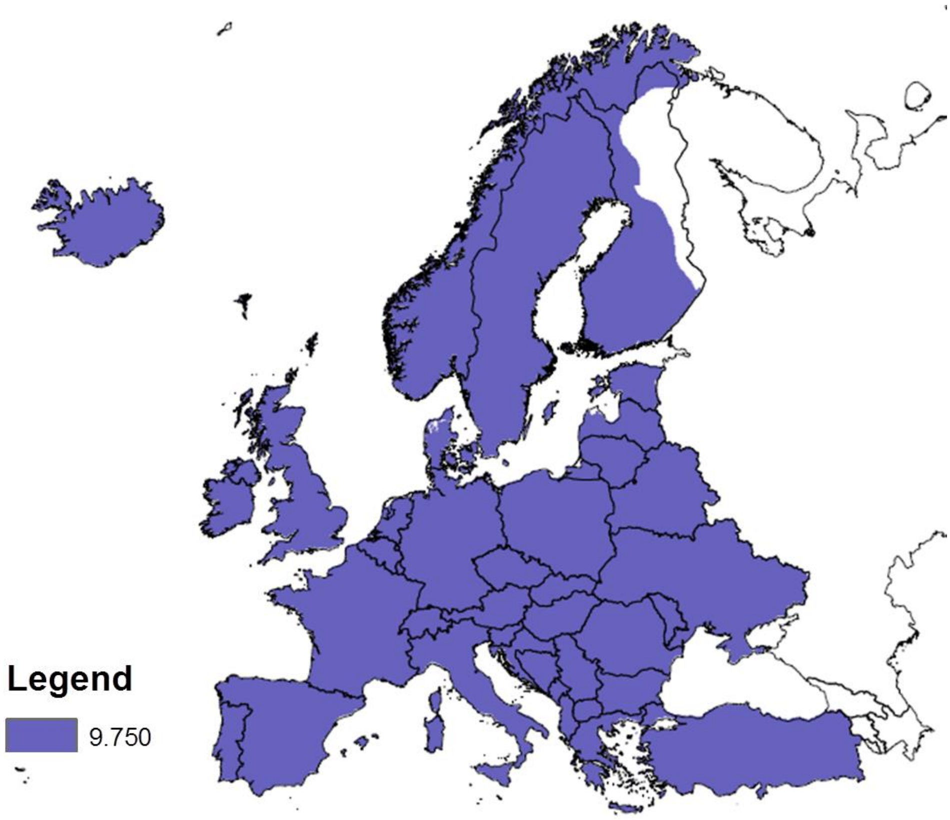

Figure: Depth at which the Minimum levelized costs of Energy is found in 2050 (in m) Please note that for this scenario the depth is uniform distributed. This displays the independence of drilling depth for an economic development

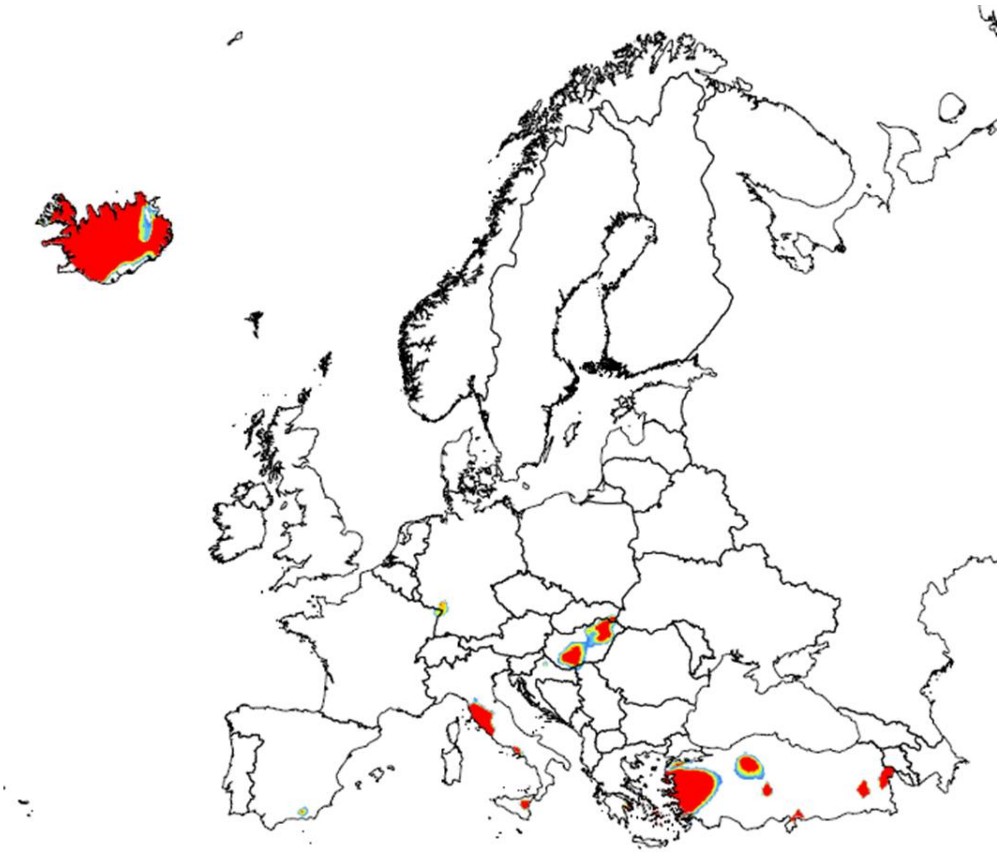

Figure: Technical Potential for a Levelized Cost of Energy in 2050 < 50 EUR/MWh (in MW/km2)

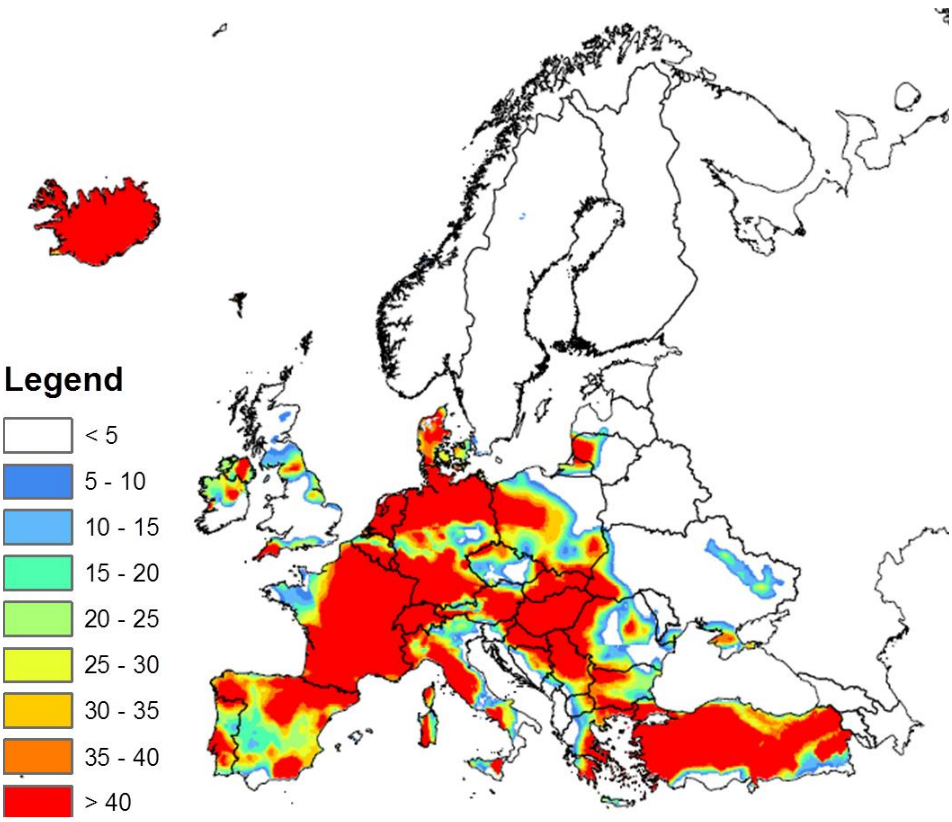

Figure: Technical Potential for a Levelized Cost of Energy in 2050 < 100 EUR/MWh (in MW/km2)

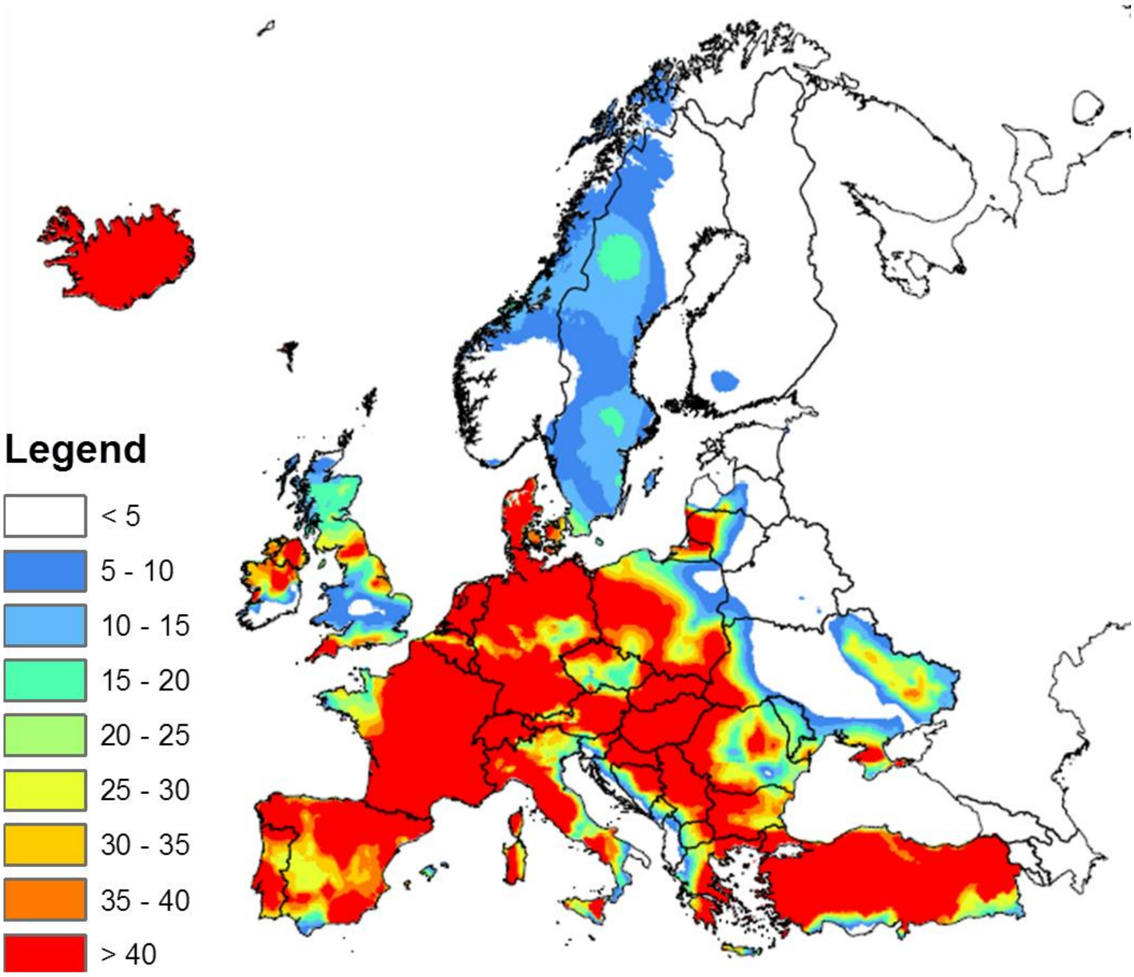

Figure: Technical Potential for a Levelized Cost of Energy in 2050 < 150 EUR/MWh (in MW/km2)