Energy 178 (2019) 419–435

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Energy technology dependence - A value chain analysis of geothermal power in the EU

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A R T I C L E I N F O

Article history:
Received 20 October 2018
Received in revised form
22 February 2019
Accepted 7 April 2019
Available online 27 April 2019

Keywords:
Energy security
Energy technology dependence
Geothermal power
Bottleneck identification
Value chain

A B S T R A C T

The majority of energy used by the European Union has been imported from non-EU countries. The EU desires to increase its own renewable energy use to secure its future energy supply. In this paper, an assessment framework of technology dependence has been proposed that can be used to locate bottlenecks in the value chain of geothermal power generation. The framework consists of an ‘above ground’ and ‘underground’ domain. It was applied to binary Organic Rankine Cycle (ORC) power plants as this type has the highest proliferation potential in the EU. The above ground domain aims to locate potential bottlenecks at a key-component level via a technology hierarchy analysis, company and trade analysis as well as a survey. The underground domain focuses on the potential bottlenecks embedded in the geothermal drilling industry by means of a drilling industry screening, rig screening and a survey. The results suggest that some Binary-ORC key-components may require attention. Furthermore, the geothermal drilling industry's dependence on the oil and gas industry can be seen as a major dependence bottleneck that might jeopardize the future proliferation of binary-ORC technologies in the EU.

1. Introduction

In 2016, the European Union imported 54% of gross energy consumption from non-EU member states. Its import dependency is particularly high for crude oil (88%) and natural gas (70%) [1]. The first oil crisis in 1973 and interruption of European natural gas supplies caused by the Ukraine-Russia natural gas conflict in 2009 have shown that the European Security of Energy Supply (SES) could be jeopardized by and vulnerable to geopolitical and economic shocks [2,3]. Since then energy security has been put in the top of the EU discussions and its member states' energy policies. In response to these concerns, the European Commission has proposed its Energy Security Strategy in 2014 with short and long-term measures. The strategy, in general, covers striving for saving energy, more locally produced energy, a better energy infrastructure, enhanced energy import strategies and common goals during energy negotiation processes [4]. It aims to ensure a stable and abundant supply of energy for European citizens and the economy.

The term Energy Security has been often recognized as difficult to define. Diverse indicators have been formulated and assessed [5–7]. A widely accepted definition is from the International Energy Agency (IEA) as “the uninterrupted availability of energy sources at an affordable price” [8]. It is important to distinguish two major forms of energy security on the basis of the Supply Chain (SC) of energy sources [4]. The first form considers safeguarding the supply of primary fuels, used for *direct* energy conversion and use (e.g. crude oil, natural gas and solid fuels). The second form elaborates on securing the materials or components used for the construction of energy technologies, so materials and components for *indirect* energy use (e.g. iron ore for a wind turbine nacelle). Among all the discussion, there is a consensus around the fact that energy dependence can be considered the most important indicator of energy security, since it is a direct threat to energy security, and consequently to a country's security [9,10].

The focus of reducing energy dependence has been traditionally given to fossil fuels as the fact that they are the only element facing the risks of external dependence. A number of studies measured and monitored energy dependence by investigating the diversity and fossil fuels import dependence [11,12]. Except for biomass, renewable energy sources such as wind, solar and geothermal, are regarded as freely available with no external dependence in energy security indicators [10,13,14]. However, renewable energy technologies (RETs) are a part of Global Value Chains (GVC) meaning their activities and resources might be outsourced in countries

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https://doi.org/10.1016/j.energy.2019.04.043
0360-5442/

Abbreviation

BOP	Blow out preventer
ESP	Electrical submersible pump
EGS	Enhanced geothermal system
EIA	Energy information administration
GVC	Global value chain
IEA	International geothermal association
ORC	Organic rankine cycle
PDC	Polycrystalline diamond compact
RET	Renewable energy technology
SES	Security of energy supply
SC	Supply chain
VC	Value chain
WEO	World energy outlook

outside the EU. Therefore, certain risks related to the deployment of RETs exist in terms of energy security. A few studies applied the approach of value chain (VC) analysis to identify potential bottlenecks of specific RETs (wind and photovoltaics). Critical materials have been found that could endanger future deployment of these technologies [15,16]. Note that external dependence is not necessarily disadvantageous for a certain energy technology. The increasing globalisation of the past decades in many cases increased the robustness of EU infrastructure, with the presence of sufficient external manufacturers and suppliers [17]. However, this argument is not applicable to any situation. External dependence could be high or the supply side of the market could be dominated by a few miners, manufacturers or countries. These situations will be defined as 'critical dependencies'. One example is that in 2012, 75% of the components for the construction of solar panels were imported from China to the EU [1]. Renewable energy technologies serve as a sustainable solution in combating climate change and decreasing dependence on fossil fuels. Geothermal energy has not until recently become a significant source of electricity and heat with prosperous development in countries such as Iceland, Italy and the USA [18]. Over the last five years, a substantial number of projects has been developed throughout the EU, and geothermal power is on its way to become an important player in the EU energy mix [19]. Studying the field of RET dependency is new and upcoming and a shared methodology with regard to this field is lacking. The aim of this study is to partly fill this knowledge gap by proposing an integrated framework to assess the dependence of geothermal power technology. Geothermal power rather than heat is selected due to increasing interest in geothermal power generation with binary Organic Rankine Cycle (ORC), which extends the scope of application to areas with lower temperature heat. To facilitate the development of the assessment framework, a literature review on geothermal power is firstly carried out (section 2). The focus of the review is to provide both an overview of the current applications of geothermal power and to identify the most promising technology types. The framework is applied in the context of the EU (section 3) and enables the policymakers to locate bottlenecks within the energy value chain of geothermal power. Results and discussion in section 4 and are followed by conclusions in section 5.

2. Literature review on the geothermal power development

2.1. Characteristic of geothermal power

Geothermal power generation has certain technical advantages compared to other RETs. Unlike wind energy (wind speed and direction) or solar energy (intensity and temperature), geothermal power does not rely on variable energy output due to changing weather conditions [20]. Partly because of that, geothermal power is a 'base-load' power source, meaning that it can generate power with a constant power output. This makes most geothermal power plants a reliable addition to the electricity grid. Very important, geothermal power plants have a relatively high capacity factor, even higher than conventional thermal plants, of 90%–95% [21,22]. From an economic point of view, geothermal power is a relatively cheap technology. The levelized cost of electricity (LCOE) production of geothermal is close to onshore wind power (e.g. 0.057 €/kWh) [23].

There are, however, also certain general disadvantages with regard to geothermal power generation. First of all, geothermal power is highly location dependent as a direct result of geological variation and distribution of thermal reservoirs. Nowadays, the importance of location dependence decreased due to the more frequent implementation of binary power plants [24,25]. Secondly, drilling costs still account for the largest share of total project costs [19]. Considering hydrothermal reservoirs, geothermal drilling practices generally account for 30%–50% of the total costs of the power generation project [26]. Within this range, drilling costs for binary power plants are relatively low, as the reservoirs are located closer to the surface. For enhanced geothermal system (EGS) projects, drilling costs could account for up to 70% of the total project costs [26,27]. In general, geothermal power can be seen as one of the cleanest forms of power generation. However, it is not free of environmental impacts. The release of non-condensable gases coming from the geothermal fluid, with typical components such as CO_2 and H_2S, is a result of decreasing the pressure in dry steam or flash plants [28]. This problem usually does not occur in binary plants, as these plants operate with a 'closed loop' system. In addition, the operation of a geothermal power plant in an inconsiderate way could reduce reservoir productivity, cause reservoir depletion and (in some cases), cause seismicity at the local level [29].

2.2. Current status of geothermal power in the EU

Geothermal power generation in Europe is a relatively new phenomenon. Prior to 1990, only a small number of geothermal power plants were operating in Europe (mainly in Italy and Iceland). These locations are suitable for dry-steam technologies. Gradually, geothermal power plant design and technology are improved, which made power generation less location-dependent. The main technology breakthroughs that initially accelerated the implementation of geothermal power plants are flash and binary technologies. The latter enables power generation from low-enthalpy reservoirs. Nowadays, geothermal power plants slowly start to emerge almost everywhere in Europe [18,19]. Table 1 shows the status of geothermal power generation in both Europe and the EU by the end of 2016.

By the end of 2016, a total number of 102 geothermal power plants operated in Europe. The total installed capacity was 2.5 GWe, of which 1 GWe in the EU. Note that the installed capacity in the countries Iceland and Turkey accounted for more than 50% of the total installed capacity in Europe. There is a significant difference in average generation capacity of the plants in each region. For Iceland, the average generation capacity per plant is about 83 MWe while for the EU it is about 19 MWe. This can be explained by the underlying geological controls, which generally favours the development of geothermal energy than many other countries in the EU.

This can be explained by the underlying geological conditions, which are generally more favourable than the conditions of many

Table 1
Geothermal power plant in Europe and the EU by the end of 2016 [18,19].

Region	Country	Plants in operation	Installed capacity (MWe)	Gross electricity production (GWh)	Plants under development
EU	Austria	2	1	2	0
	France	3	17	102	2
	Germany	9	40	61	4
	Italy	36	916	6188	1
	Portugal	2	29	175	1
	Romania	1	0.4	0.4	0
	Hungary	0	0	0	3
	Croatia	0	0	0	2
	Belgium	0	0	0	1
EU in total		53	1002	6528	14
Others	Iceland	8	663	5003	2
	Turkey	41	853	854	10
Europe in total		102	2518	12385	26

other countries in the EU.

Fig. 1 shows the number and installed capacity of different technologies in Europe and the EU respectively. It can be seen that the number of dry steam power plants accounts for roughly 60% of all operational plants in the EU. However, for Europe, the largest group is binary-ORC (50%). Binary plants represent the fastest growing group of geothermal plants mainly because they are suitable for reservoirs with a relatively low temperature and this reservoir type is the most common. It has been observed that the current trend leans towards more use of lower-temperature resources and binary plants [30]. Moreover, resources for binary plants are more prevalent [22]. It is a consensus from the current studies that binary plants are already relatively mature and the costs will decrease to competitive levels as capacities increase [19,31,32].

2.3. Potentials of geothermal power in the EU

Current studies on the potential of geothermal power in the EU have been reviewed. The results indicate the possible scale of geothermal power in future EU energy systems (see Table 2).

The Joint Research Centre (JRC) of the EU used the JRC-EU-TIMES model for four scenarios: reference, low cost, high cost and best case [22]. The low-cost scenario assumed a 6% and 21% cost reduction for ORC systems, with or without EGS respectively, while the high-cost scenario assumed 15% and 21% higher costs. The best case scenario embedded a 50% reduction of drilling and power plant costs compared to the reference scenario. For all projections, a strong increase of geothermal power production is observed (from 6.5 TWh in 2016 to 155–1100 TWh in 2050), especially in the low cost and best case scenarios. As comparison EGEC (2014) gives economic potentials of geothermal power for the years 2020, 2030 and 2050 as 21.2 TWh, 34 TWh and 2570 TWh respectively [26].

The economic potential in the study is defined as the realistic fraction of heat in the subsurface that is suitable for power production. It can be translated into economic values by using the LCOE [26]. The cut-off LCOE used for the year 2020, 2030 and 2050 is 200, 150 and 100 EUR/MWh respectively. A remarkable increase in the potential between 2030 and 2050 is observed with an average increase of 127 TWh per year. This is related to the assumed learning curve of the power plant technologies and the rapid implementation of binary power plants which are less location dependent. Finally, we included the World Energy Outlook (WEO) 2016 scenarios: current policy (CPS), new policy (NPS) and 450 (450 S) [33]. The NPS is the main scenario and takes into account policy targets and intentions that have been announced. The CPS only takes into account the policy measures which have been adopted as of mid-2016. Lastly, the 450 S scenario can be seen as the main decarbonisation scenario. It embeds the policies that aim for an average global temperature increase that does not exceed 2° Celsius. With these ambitions, 450 S has the highest implementation in the year 2040, with 28 TWh. This amount is relatively low compared to the other studies, which could be due to different costs assumptions used in the WEO projections and the related competition with other renewable energy technologies. The potential of EGS in Europe was evaluated by Limberger et al. [34]. The subsurface temperature (to a depth of 10 km) is the main parameter in determining the theoretical potential of EGS. A similar cut-off values as EGEC (2014) study have been applied to limit the technical potential, resulting in an economic potential for Europe of 19 GWe in 2020, 22 GWe in 2030, and 522 GWe in 2050.

The Binary-ORC technology has been largely embedded in the scenario constructions of current geothermal power potential studies. It is, therefore, selected as a key technology of geothermal power plant for the remaining investigation of this study. The choice has been made also because of other reasons. First, the

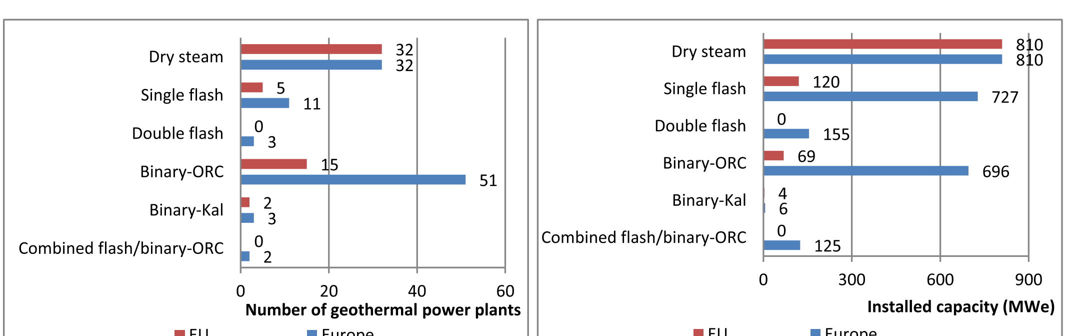

Fig. 1. Number of operational plants (left) and installed capacity (right) in Europe and the EU by 2016 [19].

Table 2
An overview of geothermal power potentials in the EU.

Studies	Scenarios	Geothermal power production (TWh)				Capacity installation (GWe)			
		2020	2030	2040	2050	2020	2030	2040	2050
[22]	Reference scenario	5.6			540	0.9			72
	Low cost Scenario	5.6			1050				
	High cost scenario	5.6			155				
	Best-case scenario	5.6			1100				150
[26]	Not defined	21.2*	34*		2570*	1.4			
[33]	Current Policies	8	11	14		1	1	2	
	New Policies	8	14	20		1	2	3	
	450 Scenario	8	18	28		1	2	4	
[34]	Theoretical potential					14000	14000		22000
	Economic potential					19	22		522

(*Results are the economic potentials instead of projection results).

Binary-ORC technology can be seen as the technology compatible with most thermal reservoirs. Even reservoirs with temperatures lower than 150 °C are suitable with the application of working-fluid based heat exchanger. This type of reservoir is the most common and makes the Binary-ORC technology the fastest growing of all geothermal power plant types. Second, drilling costs for this technology are relatively low, as the reservoirs are located closer to the surface. Finally, binary power plants are less harmful to the environment. Due to the closed-loop system, the geothermal brine (or gases released from the geothermal fluid) will not get into contact with the surface environment and the discharge of non-condensable gases does not occur.

3. Methodology

3.1. Conceptual assessment framework

The value chain elements of geothermal power generation are simplified and illustrated in Fig. 2 [35]. The development of the assessment framework was largely inspired by the concept of the VC. By using the VC a complete coverage can be achieved from material production and input to recycling and disposal. To make the scope of the framework workable and relevant, we limit the focus on two of its parts: *production of materials and components* and *drilling and installation*. These parts were chosen because the activities in red are mostly carried out by local service providers, which makes them site-specific. Data with regard to these activities are hard to find and not easily replicable (comparison with the rest of the data). To better structure the activities and facilitate the analyses, we made a distinction between the *above-ground* and *underground* domain.

The above-ground domain covers all the VC activities taking place above ground, in which the geothermal power plant is a leading object. The underground domain includes all the underground-related activities (drilling and the drilling industry). The assessment frameworks for the two domains have been developed separately as significantly different activities are involved. The main objective of the above ground domain within the framework was to screen and assess the key technology in terms of availability of products and components. The underground domain targeted a more dynamic field and covered the existing drilling market structures. Fig. 3 represents the conceptual framework of assessing technology dependence of geothermal power in the EU. It consists of research steps and applied indicators. The indicators are aimed at identifying possible bottlenecks for the supply of the materials, components and technologies used for the construction of geothermal power plants, which could threaten its deployment in the EU. This is in line with the explanation given in the introduction to the security of *indirect* energy use, which elaborates on the safeguarding of materials or components used for the construction of energy technologies.

3.2. Above ground domain

The main objective of the *technology hierarchy analysis* was to form a robust and reliable research technology classification (or hierarchy). By doing so, the technology supply chain of the Binary-ORC technology was mapped. The analysis focused on breaking down the Binary-ORC technology into one main category (key-components) and two sub-categories (sub-components) and materials. The key-component breakdown was carried out based on data collection and processing of the indicators in Fig. 3. The project cost share of each component was chosen for a particular reason. The higher the component cost relative to the overall project costs, the more likely a possible supply-constraint (bottleneck) affecting overall technology proliferation will arise. The technology hierarchy services as a foundation for bottleneck identification throughout the study. It was visualized by using a horizontal hierarchy chart.

The aim of the *company analysis at the component level* was to provide an overview of all market players involved in the construction of the selected key-components. The indicators "production facilities in EU" and "location of headquarters" were applied in the assessment to reflect the degree of controllability, robustness and reliability of the EU key-component trade market [4,15].

In order to estimate the position of the EU as a region in terms of component construction and dependence, each key component was subjected to a *trade analysis at the component level.* It examined the balance of trade (e.g. import and export values of each key-component) between the EU and the rest of the world. A positive trade balance (or trade surplus) indicates that the EU's global

Fig. 2. A schematic diagram of VC elements for geothermal power generation.

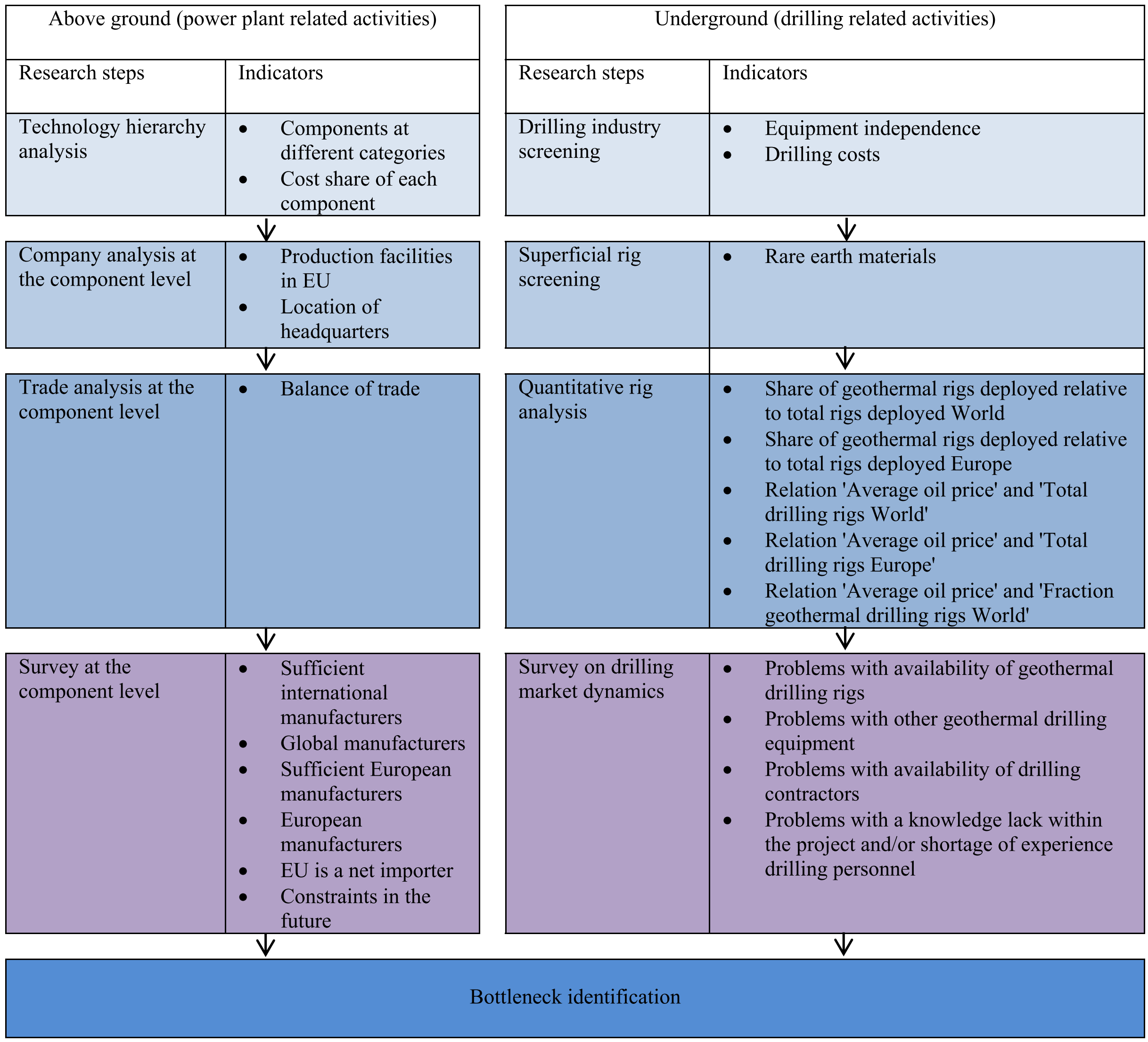

Fig. 3. Conceptual framework of assessing technology dependence of geothermal power in the EU.

market position of the key-components is favourable (and vice versa in case of a negative trade balance). The balance of the trade provides a proper indication of both the strength and independence of the market.

Finally, a survey at the component level for providing answers with regard to energy technology dependence for the above ground domain was developed. By using a questionnaire with a fixed structure (indicators in Fig. 3), information on market dynamics and field practices were gathered. The invited experts were selected from a database (expert pool) provided by the International Geothermal Association (IGA). Based on this database, it was possible to filter the experts according to their fields of expertise. By doing so, the pool of respondents could be acquainted in advance and the right questionnaire could be allocated to the right experts (two questionnaires were composed, e.g. above ground and underground). An overview of the filtered expert pool is presented in Appendix A. The full questionnaire can be found in Appendix B.

3.3. Underground domain

The technology dependence assessment of the underground domain was designed differently compared with the above ground domain. It is mainly because of the fact that drilling is the dominant activity during underground geothermal resource exploitation. The first research step *drilling industry screening* investigated background on the current market status of the geothermal drilling industry. Information provided by this analysis provided insights for the identification of one or more potential drilling industry bottleneck(s). The indicator of drilling equipment independence and drilling costs were chosen to reflect the maturity of the geothermal drilling industry [9,12].

In the step of *superficial rig screening*, geothermal drilling rigs were screened at the level of key components and materials with the occurrence of rare earth materials indicator. In case any rare earth materials are found, they will be marked as potential bottlenecks in the analysis.

A *quantitative rig analysis* was carried out after the superficial rig screening to investigate the influence of the oil and gas industry on the availability of rigs suitable for geothermal drilling operations. The analysis consisted two activities: firstly data on the global and European deployment numbers of geothermal drilling installations was investigated, and secondly, the relation between the crude oil price and rig availability in Europe was quantitatively analysed.

For the second activity, a Spearman rank correlation coefficient method was applied as it measures the strength and direction of the association between two ranked variables [36]. In order to find out how well the ranks correlate, the data for each parameter is ranked in its application. One of the advantages of this method is that it is able to assess data calculated in different ways [37]. Such characteristic is essential when comparing data sets with a different entity, e.g. oil prices and rig count (or fractions). For the Spearman rank correlation coefficient method, the general formula for variable sets (without ties) has been used according to equation (1). First, the data for both parameters (crude oil price] and [variable of rig availability) were ranked for each month of a specific year. Second, the difference (D) between the ranks of both variables was calculated and squared (D^2). This was done for every month within the specific time period ($\sum$). By doing so, one ends up with the total sum of the difference squared which, according to equation (1), should be multiplied by six ($6\sum D^2$). After that, $n(n^2-1)$ should be calculated, which was done by using the number of data pairs (n).

$$\rho = 1 - \frac{6\sum D^2}{n(n^2-1)} \tag{1}$$

where:

ρ = Spearman rank correlation coefficient
D = the difference between the ranks
n = the number of data pairs

Similar to the above ground domain, a *survey on drilling market dynamics* was developed for the underground domain. By using the indicators shown in Fig. 3, information on market dynamics and field practices were collected. Similar to the above ground domain, a list of experts has been selected and invited based on their expertise in the geothermal drilling industry. The list of involved respondents was listed in Appendix A and the full questionnaire can be found in Appendix C.

3.4. Bottleneck identification

As explained before, both above ground and underground domains consist of a specific set of analyses to provide a foundation for bottleneck exposure. The results generated from the previous steps were processed and discussed. For each research step, areas of special interest were highlighted with either “yes” (extra attention needed) or “no” (no extra attention needed). The areas which require special attention became subject of further analysis in the bottleneck identification.

4. Results and discussion

4.1. Above ground domain

The first step was the *technology hierarchy analysis* to select key and subcomponents of the above ground domain (see Fig. 3). A 5 MWe geothermal doublet binary-ORC power plant (one production and one re-injection well) was selected as the example project to investigate the financial contribution to the overall project costs [19]. For this example project, drilling costs represent about 55% of total costs, above-ground equipment was about 25% and construction and other costs were about 20% of the total costs. The four selected key-components are (1) turbine/generator unit (often seen as one integrated component) (50% of above ground equipment costs), (2) injection pumps (i.e. Electrical Submersible Pump (ESP[1])) (12%), (3) heat exchangers (8%) and (4) cooling tower (8%).

The subcomponents are formed based on the equipment list (see Appendix D) of binary geothermal power plants in the study [38]. For critical materials, copper was identified as a possible constraint and neodymium use in permanent magnets used in generators [39,40]. On the basis of the results, Fig. 4 displays the technology hierarchy for a binary-ORC power plant.

The second step was the *company analysis* at the component level. The results of the company analysis are discussed per key component. Fig. 5 presents an overview of binary-ORC turbine installations per manufacturer in the period 2012–2016 in the EU and Europe [19]. This period was chosen because of data availability. The manufacturers Ormat, Exergy, Atlas Copco-Exergy and Turboden can be regarded as the main installers. Out of the 32 Binary-ORC turbines installed in Europe, only 3 were installed in EU countries, in this period. This has mainly to do with the fact that the Binary-ORC market in Turkey (non-EU) flourished in the last five years. These turbines together represent 76% of all turbines currently installed in Turkey.

An overview of the leading manufacturers of the key components supplying the European market can be seen in Table 3. The selection of the manufactures has been made on the basis of [19]. All data is extracted from company websites. It is observed that the majority of the headquarters of turbine manufacturers are located in the EU. In terms of heat exchangers, six of the nine manufacturers has a headquarter located within the EU and many production facilities are also located in the EU. This result is in line with the status that the European market has always been strong for heat exchangers [19]. It is noticeable that all of the ESP manufacturers subjected to this research have their headquarters located in non-EU countries. On the basis of available data, the number of production facilities of ESP located in the EU is limited. For many of these discussed companies, they are also global manufacturers of the valves, control and monitoring systems associated with fluid lifting mechanisms [19]. It is clear that producing ESPs is not the core business. Similar to the ESP manufacturers, all cooling tower manufacturers selected in this study have their headquarters located in non-EU countries. Also, the number of production facilities located in the EU is limited.

The third step was the *trade analysis* to identify the trade flows of components between the EU and the rest of the world. All component specific data was provided by the database of United Nations Commodity Trade Statistics [41]. Trade data was collected for the period between 2012 and 2017. No datasets are available that specifically focus on binary-ORC turbines and generators, therefore the following datasets were applied in the analysis:1) ‘Steam turbines & other vapour turbines (excl. for marine propulsion), of an output <40 MW’ (code: 840682); 2) ‘AC generators of an output > 750 kVA’ (code: 850164); 3) ‘Heat exchange units, non-domestic’ (code: 841950); 4) ‘Centrifugal pumps’ (code: 841370); 5) ‘Air conditioning machines, comprising a motor-driven fan and elements for changing the temperature and humidity, including those machines in which the humidity cannot be separately regulated’ (code: 41510). The dataset for the turbine was chosen as the current installed Binary-ORC plants in the EU and Europe have the average capacity of 5 MWe and 13.5 MWe respectively (see Fig. 1). This range is also in line with the average capacity worldwide, which is 6.3 MW [42]. Similar reason applies to the selection of the generator dataset as the generator for Binary-ORC geothermal power plants generally falls in the range between 1000 kW and 10000 kW. Other selected datasets have broad range coving the

[1] ESP is an artificial-lift method for lifting moderate to high volumes of fluids from wellbores. A typical ESP system includes components such as a multi-staged centrifugal pump, three-phase induction motor, seal-chamber section, power cable and surface controls.

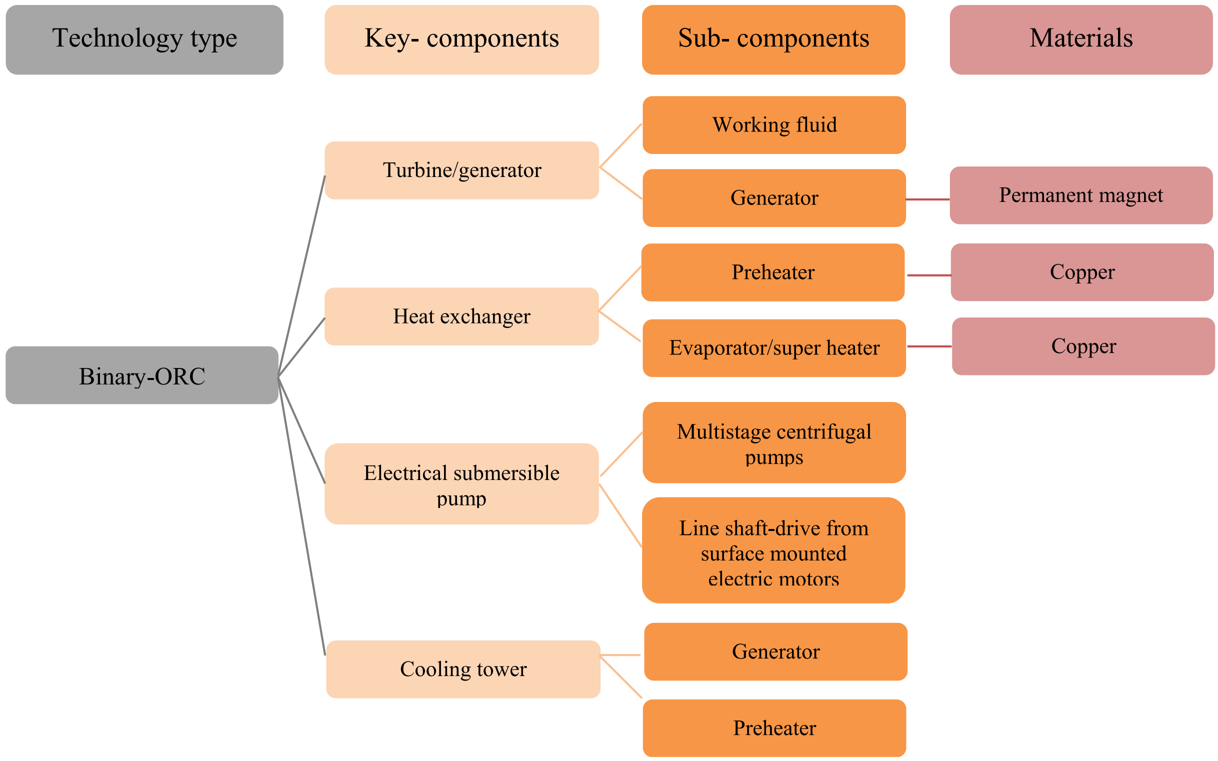

Fig. 4. Technology hierarchy for Binary-ORC power plant.

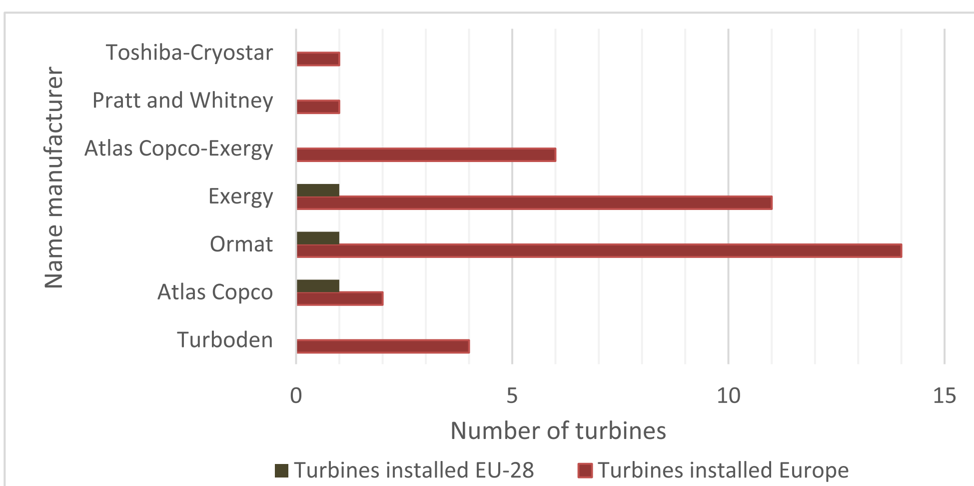

Fig. 5. Binary-ORC turbines installed per manufacturer in both Europe and the EU between 2012 and 2016.

components in all types of geothermal power plants.

A summary of the trade analysis result is listed in Fig. 6 (Appendix E shows the detailed results of the trade analysis). The trade analysis indicates that the EU is a net exporter for all examined key components, except for the cooling equipment, which has a negative trade balance. Even though the applied datasets were not specific for Binary-ORC plants only, the results provide general indications of the strength and independence of the market.

The last step was the *survey* on binary-ORC key components. The survey has been completed by 12 respondents, of which seven respondents have experience in project management regarding binary geothermal power plant assembly. Table 4 provides an overview of the summarized answers that were given and the possibility of bottlenecks. According to the respondents, the cooling tower is the only key component that is free of potential bottlenecks. The other key-components all have some bottlenecks that might occur, mainly in the area of the number of manufacturers and their market position. This differs from the trade analysis (cooling tower only component with trade deficit). A first hypothesis for this discrepancy could be that for the cooling tower trade analysis, the UN Comtrade category ‘Air conditioning machines, comprising a motor-driven fan and elements for changing the temperature and humidity, including those machines in which the humidity cannot be separately regulated; parts thereof’ has been used. This category is very broad and it is most likely that the percentage of cooling towers used for geothermal power plants in this dataset is small.

Table 3
Details of component learding manufacturers.

Company name	Total production facilities	Production facilities in EU	Share of production in EU	Location Headquarters
Turbine				
Ormat	>1	0	0%	Non-EU
Exergy	2	1	50%	EU
Atlas Copco-Exergy	5	1	20%	EU
Turboden	1	1	100%	EU
Heat exchanger				
Alfa Laval AB	42	22	52%	EU
Danfoss & Sondex Holdings A/S	69	36	52%	EU
Kelvion Holdings Gmbh	49	32	65%	EU
SPX Corporation	28	5 or less	n/a	Non-EU
Xylem Inc.	n/a	n/a	n/a	Non-EU
Gunter AG & Co. KG	8	3	38%	EU
Hamon & Cie international SA	3	1	33%	EU
Modine manufacturing company	n/a	n/a	n/a	Non-EU
SWEP international	5	2	40%	EU
Electrical Submersible Pump				
Schlumberger	17	4	24%	Non-EU
Baker Hughes	>20	3	n/a	Non-EU
GE Oil & Gas	n/a	n/a	n/a	Non-EU
ITT/Goulds	12	1	8%	Non-EU
Canadian ESP	1	0	0%	Non-EU
Flowserve	10	5	50%	Non-EU
Halliburton	16	n/a	n/a	Non-EU
Weatherford International	50	n/a	n/a	Non-EU
Borets company	7	1	14%	Non-EU
Cooling tower				
Dow Chemical company	214	n/a	n/a	Non-EU
GE Power	n/a	n/a	n/a	Non-EU
Babcock & Wilcox	9	3	33%	Non-EU
SPX	28	5 or less	n/a	Non-EU
Ecolab/Nalco	11	3	27%	Non-EU
ETC Ltd.	n/a	n/a	n/a	Non-EU

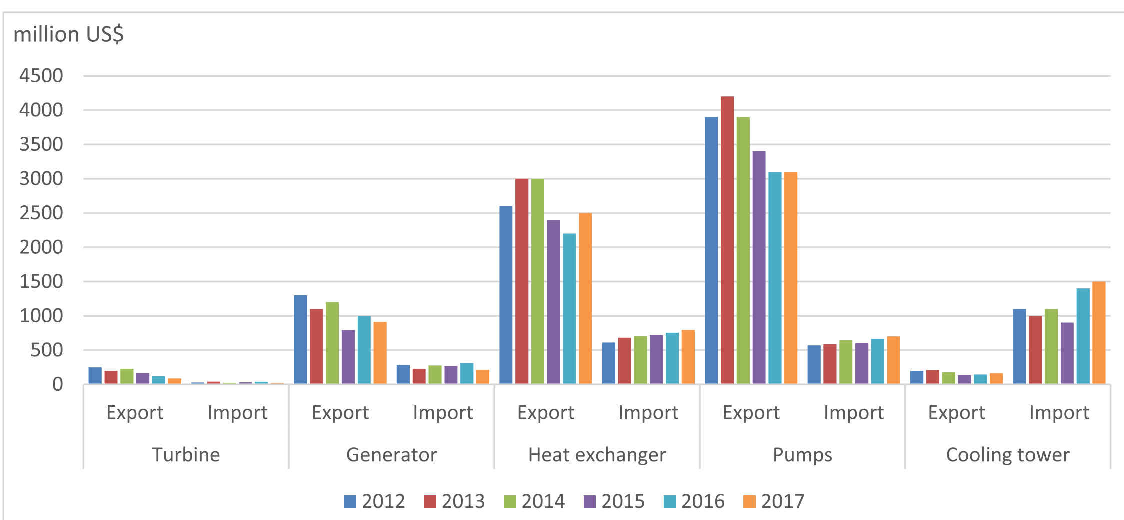

Fig. 6. Import and export value of the key components in the EU between 2012 and 2017.

Therefore, it might not be representative for Binary-ORC cooling towers. Apparently, a trade deficit does not cause any problems for Binary-ORC power plant construction in practice. A second hypothesis could be that the number of respondents was too small in order to be representative for the whole industry.

4.2. Underground domain

The first assessment step of the underground domain was *the drilling industry screening* focusing on drilling equipment and costs. Data were mainly collected from the EGEC reports [19,26,43]. It is found that the geothermal drilling industry cannot be seen as a free-standing industry. On contrary, it largely depends on drilling equipment provided by the hydrocarbon industry. Rig availability, a major concern regarding equipment dependence, cannot always be guaranteed in geothermal drilling projects. Most of the time, a rig has to be borrowed from the hydrocarbon industry. It is observed that the drilling cost is directly dependent on the crude oil prices. A drilling cost index and the crude oil barrel price from 2000 to 2012 were depicted showing a clear correlation between these two [26].

Table 4
A summary of the survey results of the above ground domain.

Key component	Question	Answer	Answer share	Bottleneck (−/+)*
Turbine/Generator	Sufficient international manufacturers	No	57.1%	−
	Number of global manufacturers (average)	10	n/a	+
	Sufficient European manufacturers	No	74.1%	−
	Number of European manufacturers (average)	4	n/a	+
	Global market position European manufacturers	Poor	57%	−
	EU is a net importer	Yes/No	50%	+
	Constraints in the future (average)	5,9	n/a	+
Heat Exchanger	Sufficient international manufacturers	Yes	71.4%	+
	Number of global manufacturers (average)	20	n/a	+
	Sufficient European manufacturers	Yes/No	50%	+
	Number of European manufacturers (average)	8	n/a	+
	Global market position European manufacturers	Poor/Average	57.1%	−
	EU is a net importer	Yes/No	50%	+
	Constraints in the future (average)	5,7	n/a	+
Electrical Submersible Pump	Sufficient international manufacturers	No	57.1%	−
	Number of global manufacturers (average)	7	n/a	+
	Sufficient European manufacturers	No	71.4	−
	Number of European manufacturers (average)	3	n/a	+
	Global market position European manufacturers	Poor/Average	85.8%	−
	EU is a net importer	Yes	57.1%	−
	Constraints in the future (average)	5,9	n/a	+
Cooling Tower	Sufficient international manufacturers	Yes	100%	+
	Number of global manufacturers (average)	24	n/a	+
	Sufficient European manufacturers	Yes	100%	+
	Number of European manufacturers (average)	7	n/a	+
	Global market position European manufacturers	Average/Good	85.8%	+
	EU is a net importer	No	57.1%	+
	Constraints in the future (average)	4,6	n/a	+

(* potential bottlenecks are indicated with -).

It indicates the influence of the oil and gas industry on the geothermal drilling costs. Moreover, two problems often occur in the geothermal projects: 1) rigs are not often available for geothermal drilling practices and 2) project costs are high as a result of the high rent prices for drilling equipment. However, the direct effect of the oil price on rig availability is unclear and a clear relationship between the drilling cost and rig availability is still lacking.

In the second step, a *superficial rig screening* was carried out at the level of key components and materials with the indicators of occurrence of rare earth material. During the analysis, no critical material has been identified in the standard drilling setup. Most of the components are made out of bulk material such as steel [44]. An exception is the Polycrystalline Diamond Compact (PDC) drill bit, which contains synthetic diamond. Producing synthetic diamond involves the heating of carbon under extremely high pressure and temperature. It is not likely that PDC production would hinder geothermal drilling rig deployment, as carbon is a bulk material of which the earth has sufficient reserves.

A *quantitative rig analysis* was further carried out to investigate the influence of the oil and gas industry on the availability of rigs for geothermal drilling operations. Worldwide and European rig count data was collected from the company Baker Hughes to analyse drilling rig deployment [45]. As one of the largest oilfield services companies, it keeps track of the number of drilling rigs that were deployed each month since 1975. Table 5 shows monthly rig count data of the world and Europe in 2016 and the first quarter of 2017. It can be seen that the deployed geothermal drilling rigs have a small share in total rigs account. Such share was on average 20.4% in Europe and 4.2% globally during 2016 and the first quarter of 2017.

The Spearman rank correlation coefficient method was applied to analyse the relationship between the crude oil price and rig availability. For historical oil prices, data was collected from the U.S. Energy Information Administration (EIA) [46]. Data on rig availability was again, taken from Baker Hughes [45]. Instead of absolute numbers, the fraction of geothermal rigs of the total rig number for the selected time period was used. It was done to provide better an understanding of geothermal rig availability. The time period between 2014 and the first quarter of 2017 has been chosen to investigate the correlation. The results (see Table 6) indicate strong correlations between the examined variables. It can be seen that an increase in oil prices correlates to an increasing deployment rate of drilling rigs and a decreasing fraction of rigs used for geothermal drilling. In relation to market dynamics, these findings may be interpreted as: an increase in crude oil prices leads to a decrease of financial power in market competition for geothermal drilling projects, and consequently, the chance of acquiring geothermal drilling rigs becomes low. These results again show that dependence of the geothermal drilling industry on the oil and gas industry is large. An exacerbating factor is that oil and gas projects typically include the drilling of multiple wells, which increases the attractiveness of these projects. The time series data behind Table 6 can be found in appendix F.

As the last step in the underground domain, *the survey* on drilling market dynamics in the geothermal drilling industry in Europe has been filled in by 11 respondents of which 9 have participated in a geothermal drilling project in an EU member state. The survey results are summarized in Table 7.

A majority of respondents indicated the issue of availability of geothermal drilling rigs. Two responses elaborated that: “When the oil price is high, the rigs are engaged with a high price”, “No rig because of the high oil price” and “Availability scarcity is due to the price of oil and gas”. Less concern was indicated for other drilling equipment, for example ‘cement for casing’ (2 times), ‘blow out preventer (BOP)’ (3 times) and ‘packer, mobile equipment’ (1 time) were indicated a couple of times. Availability of drilling contractors was indicated as a problem with 56% of the respondents. The responses were again related to oil and gas activities: “High cost to transport rig to the destination and demobilization fees”, and “Oil

Table 5
The deployment of rig in the world and Europe [45].

Month	World			Europe		
	Total rigs	Geothermal rigs	Percentage (%)	Total rigs	Geothermal rigs	Percentage (%)
01–2016	1045	38	3.6%	108	20	18.8%
02–2016	1018	40	3.9%	107	22	20.5%
03–2016	985	38	3.8%	96	16	17.0%
04–2016	946	37	3.9%	90	16	18.0%
05–2016	955	41	4.3%	95	18	19.4%
06–2016	927	40	4.3%	91	18	20.1%
07–2016	938	43	4.6%	94	18	19.4%
08–2016	937	43	4.6%	96	21	22.0%
09–2016	934	43	4.6%	92	20	21.8%
10–2016	920	43	4.7%	87	25	28.3%
11–2016	925	39	4.3%	97	22	23.1%
12–2016	929	39	4.2%	99	22	22.2%
01–2017	933	47	5.0%	98	25	25.8%
02–2017	941	41	4.4%	107	19	18.1%
03–2017	943	35	3.7%	94	16	17.1%
04–2017	956	34	3.6%	91	14	15.2%
Average	**952**	**40**	**4.2%**	**96**	**20**	**20.4%**

Table 6
Correlation between average oil prices and drilling rigs.

Variables	Period	Spearman's Rho	
		value	Indication
Average oil price and Total drilling rigs World	1-14/3-17	0.71	Strong
Average oil price and Total drilling rigs Europe	1-14/3-17	0.70	Strong
Average oil price and fraction geothermal drilling rigs World	1-14/3-17	−0.74	Strong
Average oil price and fraction geothermal drilling rigs Europe	1-14/3-17	−0.78	Strong

Table 7
A summary of the survey results of the underground domain.

Question	Answer	Share	Bottleneck (−/+)*
Problems with availability of geothermal drilling rigs	Yes	67%	−
Problems with other geothermal drilling equipment	No	62.5%	+
Problems with availability of drilling contractors	Yes	56%	−
Problems with lack of knowledge within the project and/or shortage of experience drilling personnel	Yes	67%	−

(* potential bottlenecks are indicated with -).

and gas pays better and has more extensive drill jobs. A contractor prefers to contract a job for 10 wells, instead of a contract for one well with a high chance for a second one", etc. In addition, lack of knowledge and personnel was also pointed as "This is one of the biggest problems in the geothermal well drilling project today in my opinion. I have personally had to train oil and gas experienced personnel in geothermal drilling procedures on almost every new project I have been on.", "Just a few German-speaking Drilling Supervisors available." and "Not enough experienced drilling personnel available in Switzerland". Some of these responses illustrate that the competition with oil and gas projects is partly related to contract size, in terms of the amount of wells to be drilled. If for geothermal projects a portfolio approach could be adopted, where a contract includes the drilling of multiple wells sequentially, this could increase their attractiveness.

4.3. Bottleneck identification

4.3.1. The above ground domain

Table 8 provides an overview of the results found for the company analysis, trade analysis and survey. According to both company and trade analyses, no extra attention is required with regard to the turbine/generator and heat exchanger market. Manufacturers of these components are well represented within the region (with regard to both production facilities and headquarters locations). In addition, both components have a positive trade balance. Some deviations have been found in the survey results. Most notably 74% of the respondents believe that there are not sufficient turbine/generator manufacturers in Europe. Furthermore, 57% of the respondents believe that the market condition for heat exchangers is poor to average. However, in the existing studies, it has been stated that "Europe has always been a strong market for heat exchangers and features most of the global leaders in heat exchanger manufacturing" [19]. It is in line with the results found in the company analysis that most of the heat exchanger manufacturers are located in Europe. Therefore, no clear turbine/generator or heat exchanger supply risk has been detected.

It is observed that the manufacturers of ESP and cooling towers are less represented in the EU. Almost all headquarters of the examined manufacturers are located outside of EU territory. Furthermore, it has been found that for most of the manufacturers, the production of ESPs and cooling towers is not the core business. In the survey, 74% of respondents indicate that there are not sufficient European ESP manufacturers. For the cooling tower, respondents indicated that there are sufficient international cooling tower manufacturers for binary power plants to meet demand. However, the average estimated number of global cooling tower manufacturers is approximately 24 of which 7 are based in Europe.

Table 8
Bottleneck indication for the above ground domain.

Component	Total production facilities	Production facilities in EU	Production in EU	Location Headquarters	Trade analysis	Survey
Turbine/generator	No	No	No	No	No	Yes
Heat exchanger	No	No	No	No	No	Yes
Electrical Submersible Pump	No	Yes	Yes	Yes	No	Yes
Cooling tower	No	Yes	Yes	Yes	Yes	No

(note: "yes" means possible bottleneck; "no" means bottleneck not likely).

This is reflected in the negative trade balance for cooling towers. The lack of manufacturing capacity and infrastructure for these components could thus potentially present risks to the wider proliferation of geothermal power generation projects in the (near) future. The interpretation of the results from the above ground survey includes clear limitations. This will be further elaborated in section 4.4.

4.3.2. The underground domain

Table 9 summarizes the identified bottlenecks for the underground domain. The results from the survey confirm what was found in the rig analyses. Clear bottlenecks are identified for the independence of drilling equipment in relation to the oil and gas industry as well as for rig availability, drilling costs and lack of sufficient knowledge.

4.4. Discussion of uncertainties

A number of uncertainties in data collection and limitations are present that may influence the results. The main ones are:

- For determining the key components in the hierarchy analysis, only component project cost share data was used. For future research, a wider range of indicators can be used for selecting key-components. Furthermore, additional sub-components and materials could be taken into account in more detail analysis as well as including component screening for the underground domain.
- The red VC elements (Fig. 2) are not included in the conceptual framework (Fig. 3). This is because these activities are mostly carried out by local service providers, which makes them site specific. Data with regard to these activities is hard to find and not easily replicable (comparison with the rest of the data). The two main focus elements of this paper are indeed more transferable/replicable/general.
- It was difficult to determine when the number of factories or head quarter's is too low or not for a certain key-component. Therefore, involving company and factory dimensions in the future research is recommended.
- For the trade analysis, general categories were used. It is not certain if these results are also applicable for the more limited subcategories applicable for binary geothermal power plant components.
- The number of respondents for the above-ground survey was lower than expected. Because the above-ground survey consisted mainly of quantitative closed questions (just one open question), it was hard to add meaning to the answers, especially in comparison to the underground survey (which included more open questions). The individual answers to the open-ended questions provided some valuable insights for the underground survey and less for the above-ground survey.
- Some research elements could not be investigated more thoroughly as they were limited by a lack of available data at the time of this research. Examples are:
  - Data with regard to local geothermal service provider's activities (as explained above);
  - Data on the availability of valuable geothermal knowledge in the region;
  - Data on possible substitutes for Binary-ORC and drilling components;
  - Cost data on components

For further research, it is suggested to conduct a case study to activities taking place in a meaningful and representative region for the EU geothermal industry. Case studies are especially valuable for bullets one and two (related to underground domain) as it will be more easy to collect data in a specific region instead of for the whole EU. For bullets three and four, it is suggested to focus on certain key-components and contact component manufacturers for detailed information on substitutes and component costs.

5. Conclusions

The main goal of this study was to develop and propose a framework of technology dependence assessment that can be used by researchers and policymakers to identify bottlenecks within the value chain of geothermal power generation. The developed framework consists of an above ground and an underground domain, which each includes specific analyses and corresponding indicators. After identifying the most promising technology (binary-ORC), a technology hierarchy analysis with key-components has been established for the above ground domain. This formed the basis for identifying bottlenecks by means of a company analysis, a trade analysis and a survey. The underground domain targeted the geothermal drilling industry. It consisted of a drilling industry screening based on literature, both a superficial and a quantitative rig analysis and a survey.

Results showed the bottlenecks in the value chains of the key-components ESP and cooling tower. These bottlenecks could be contributing and relevant for targeted future research with regard

Table 9
Bottleneck identification for the underground domain.

Bottleneck	Drilling industry and rig screening	Rig screening and analysis	Survey
Drilling equipment independence	Yes	–	Yes
Geothermal drilling costs	Yes	–	Yes
Components and materials	–	No	No
Availability of rigs	–	Yes	Yes
Knowledge	–	–	Yes

to the proliferation of the binary-ORC geothermal power generation technology. However, we regard the dependence on and influence of the oil and gas sector on the deployment of geothermal drilling rigs as a main bottleneck for geothermal power proliferation. The security of supply of geothermal power generation is dependent on developments with regard to the geothermal drilling industry. An industry which should thus be safeguarded and be subject to further studies. Policies could play an important role to facilitate the emergence of an own more independent geothermal drilling sector, where rig prices and availability are much less disturbed by changes in oil price and exploration. These policies would need to specifically target the current dependencies by providing incentives for own industry development, such as subsidies for setting up geothermal drilling equipment manufacturers in Europe.

The proposed framework and its application in this study can be seen as fruitful and contributing to policymaker's general understanding of the European security of geothermal power supply. However the framework can be further extended and improved by gathering data more specifically for the geothermal industry.

Appendix A

Table A
Filtered expert pool for the questionnaires

Respondent's name	Respondent's main expertise (Two upper expertise fields in the International Geothermal Association (IGA) expert pool list)	Respondent's Company	Operating Region (EU/Non-EU)	Suitable Questionnaire	
				Drilling	Power plants
Identities of the respondents are concealed for privacy reasons	• Structural geology • Geothermal exploration	GMX	EU	X	
	• Surface geophysics, geophysical measurements • Geothermal exploration	EGS-Energy	EU	X	X
	• Structural geology • Geothermal exploration	Cranfield University	EU	X	X
	• Geothermal exploration • Drilling operations management	Sankt Galler Stadtwerke	EU	X	X
	• Geothermal exploration • Drafting of a geothermal conceptual model	World Bank	EU	X	
	• Structural geology • Surface geophysics, geophysical measurements	University of Geneva	EU	X	X
	• Hydrogeological analysis • Reservoir modelling, monitoring, engineering	Tlalli Energia	EU	X	X
	• Surface geophysics, geophysical measurements • Hydrological measurements	Vito	EU	X	X
	• Geothermal power plant design • Geothermal power plant construction	University of Bayreuth	EU		X
	• Geothermal district heating system • Geothermal communication with stakeholders	Iceland Geothermal	EU	X	X
	• Geothermal power plant design • Geothermal power plant construction	Thorndon Cook Ltd	EU		X
	• Geothermal exploration • Drafting of a geothermal conceptual model	Geoex Hungary	EU	X	X
	• Structural geology • Geochemical fluid analysis	PanTerra	EU	X	
	• Drilling operations management • Geothermal power plant design	Powereng	EU	X	X
	• Structural geology • Hydrogeological analysis	CivicMapper	EU	X	
	• Structural geology • Geothermal exploration	Glencore	EU	X	
	• Geothermal exploration • Drafting of a geothermal conceptual model	Progeo	EU	X	X
	• Structural geology • Surface geophysics, geophysical measurements	Geotop	EU	X	X
	• Geothermal exploration • Well drilling	Keith Power consulting	EU	X	X
	• Geothermal exploration • Drafting of a geothermal conceptual model	GeoGlobal Energy LLC	EU	X	X
	• Surface geophysics, geophysical measurements • Hydrogeological analysis	Ineg	EU	X	
	• Geothermal communication with stakeholders • Geothermal lobbying/marketing	ThinkGeoEnergy	EU	X	X
	• Well drilling • Drilling operations management	Cougar Drilling Solutions	EU	X	
	• Structural geology • Surface geophysics, geophysical	HarbourDom	EU	X	
	• Geothermal district heating system • Social and environmental monitoring	IGA	EU	X	X
	• Geothermal exploration • Reservoir modelling, monitoring, engineering	National Oilwell Varco	EU	X	
	• Geothermal exploration • Well drilling		EU	X	

Table A (*continued*)

Respondent's name	Respondent's main expertise (Two upper expertise fields in the International Geothermal Association (IGA) expert pool list)	Respondent's Company	Operating Region (EU/Non-EU)	Suitable Questionnaire	
				Drilling	Power plants
	• Structural geology • Geothermal exploration	Well Engineering Partners Consultant	EU	X	
	• Structural geology • Geothermal district heating system	Navigo	EU	X	
	• Geothermal communication with stakeholders • Geothermal project management	KPMG	EU	X	X
	• Structural geology • Geochemical fluid analysis	PanTerra	EU	X	
	• Structural geology • Geothermal exploration	RwGeo	EU	X	X
	• Geothermal exploration • Reservoir modelling, monitoring, engineering	Lecturer	EU	X	X

Appendix B. A full question list for the above ground domain

Survey on main Binary-ORC power plant components (all questions are repeated per component turbine/generator, heat exchanger, cooling towers, ESP).

Please answer the following questions based on your market knowledge and industry experience.

In your opinion, are there sufficient international … manufacturers for binary power plants to meet demand?

- Yes
- No
- I don't know

Could you estimate the number of global manufacturers?

…. …. …. …. …. …. …. …. …. …. …

In your opinion, are there sufficient European … manufacturers for binary power plants to meet demand?

- Yes
- No
- I don't know

Could you estimate the number of European manufacturers?

…. …. …. …. …. …. …. …. …. …. ….

In your opinion, do you think the global market position of European …. manufacturers is.

- Good
- Average
- Poor
- I don't know

Is the EU a net importer of ….

- Yes
- No
- I don't know

On a scale from 1 to 10, how likely do you think it is that binary … supply will be constrained in the future? (due to a high dependence on non-EU suppliers) *

1	2	3	4	5	6	7	8	9	10
Not likely at all									Extremely likely

In your opinion, which binary power plant component(s) would need extra attention with regard to component scarcity on the EU market?

- Working fluid
- Feed pump
- Down-hole pump
- Control system
- Air cooling
- Brine piping

Other:

Why?

Would you like to add any remarks regarding this questionnaire?

…. …. …. …. …

Appendix C. A full question list for the underground domain

Survey on geothermal drilling.

Rig availability.

Have you ever experienced problems with the availability of geothermal drilling rigs?

- Yes
- No

What was the main cause of this problem?

Drilling equipment.

Have you ever experienced problems with the availability of other geothermal drilling equipment? (*e.g.* cement, mud pump, shaker etc.)

- Yes
- No

With which component(s) have you experienced availability problems?

- Cement for casing
- Blow Out Preventer (BOP)
- Mud Pump
- Shaker
- Drill kelly
- Generator
- Drill Bit
- Other:

What was the main cause of limited component availability?

Please name the component(s) and give corresponding explanation.

…. …. …. …. …. …. …. ….

Drilling contractors.

Have you ever experienced problems with the availability of drilling contractors?

- Yes
- No

What was the main cause of limited contractor availability?

Please give main cause and explain briefly.

…. …. …. …. ….

Knowledge and experience.

Have you ever experienced problems with a knowledge lack within the project and/or a shortage of experienced drilling personnel?

- Yes
- No

Please explain the situation briefly.

EGS.

Have you ever been involved in an EU Enhanced Geothermal System (EGS) drilling project?

- Yes
- No

With the previous questions in mind, can you think of any availability problems concerning EGS-specific operations?

…. …. …. ….

Appendix D

Table A2
Full equipment list for Binary ORC [38].

Category	System	Type
1. Downwell Pumps and motors	1.1 Multistage centrifugal pumps, line shaft-driven from surface-mounted electric motors or submersible electric pumps	
2. Brine supply system	2.1 Sand removal system	2.1.1 Solids knock-out drum
3. Brine/working fluid heat exchangers	3.1 Preheater	3.1.1 Horizontal cylinder, liquid-liquid, shell-and-tube type with brine on tube side and working fluid on shell side, or vertical, corrugated plate type
	3.2 Evaporator/super heater	
4. Turbine-generator and controls	4.1 Working fluid turbine (axial flow), generator, and accessories	
5. Working fluid condenser, accumulator and storage system	5.1 Condenser	
	5.2 Dump tank and accumulator	5.2.1 Holding tank large enough to store full capacity of working fluid charge
	5.3 Evacuation pumps to remove working fluid to storage during maintenance	
6.Heat rejection system	6.1 Wet cooling system	
	6.2 Dry cooling system (if a source of make-up water is not available)	
7.Working fluid feed pump system	7.1 Condensate pumps	
	7.2 Booster pumps (as needed)	
8. Backup systems	8.1 Standby power supply	
9. Brine disposal system	9.1 Brine return pumps and piping	
10. Fire protection system (if working fluid is flammable)	10.1 High-pressure sprinkler system	
	10.2 Flare stack	

Appendix E

Table A3
Import and Export data of the key-components in the above ground domain between 2012 and 2017

Source [41]:			Turbine		Code: 840682	
Import & Export Steam turbines & oth. vapour turbines (excl. for marine propulsion), of an output not exceeding 40 MW						
Event	Region	Trade flow	Partner Country	Net weight	Trade Value	Balance of trade
Year	Name	Im/Ex	Name	[Kg]	[USD]	+/−
2012	EU-28	Export	World	5767989	248.0 million	+
2012	EU-28	Import	World	658093	28.8 million	
2013	EU-28	Export	World	4049189	195.9 million	+
2013	EU-28	Import	World	897926	41.5 million	
2014	EU-28	Export	World	4571231	228.2 million	+
2014	EU-28	Import	World	558093	24.4 million	
2015	EU-28	Export	World	2941133	163.8 million	+
2015	EU-28	Import	World	603891	30.4 million	
2016	EU-28	Export	World	3617219	120.3 million	+
2016	EU-28	Import	World	1039394	39.4 million	
2017	EU-28	Export	World	2267633	89.0 million	+
2017	EU-28	Import	World	375816	20.1 million	
Source: [41]			**Generator**		**Code: 850164**	
Import & Export AC generators, of an output > 750 kVA						
Event	Region	Trade flow	Partner Country	Net weight	Trade Value	Balance of trade
Year	Name	Im/Ex	Name	[Kg]	[USD]	+/−
2012	EU-28	Export	World	84173012	1.3 billion	+
2012	EU-28	Import	World	32062054	281.8 million	
2013	EU-28	Export	World	78237829	1.1 billion	+
2013	EU-28	Import	World	28937439	226.4 million	
2014	EU-28	Export	World	80248590	1.2 billion	+
2014	EU-28	Import	World	33101398	276.3 million	
2015	EU-28	Export	World	134373259	791.2 million	+
2015	EU-28	Import	World	34299052	267.2 million	
2016	EU-28	Export	World	99798221	1.0 billion	+
2016	EU-28	Import	World	55111569	309.9 million	
2017	EU-28	Export	World	78494094	910.9 million	+
2017	EU-28	Import	World	33622786	212.2 million	
Source: [41]			**Heat exchanger**		**Code: 841950**	
Import & Export Heat exchange units, non-domestic, non-electric						
Event	Region	Trade flow	Partner Country	Net weight	Trade Value	Balance of trade
Year	Name	Im/Ex	Name	[Kg]	[USD]	+/−
2012	EU-28	Export	World	137027670	2.6 billion	+
2012	EU-28	Import	World	41828275	610.6 million	
2013	EU-28	Export	World	148621576	3.0 billion	+
2013	EU-28	Import	World	44320944	680.9 million	
2014	EU-28	Export	World	148900747	3.0 billion	+
2014	EU-28	Import	World	45118802	706.2 million	
2015	EU-28	Export	World	137254551	2.4 billion	+
2015	EU-28	Import	World	49387057	718.8 billion	
2016	EU-28	Export	World	122605355	2.2 billion	+
2016	EU-28	Import	World	51406188	752.9 million	
2017	EU-28	Export	World	138834728	2.5 billion	+
2017	EU-28	Import	World	49946906	794.0 million	
Source: [41]			**Cooling tower**		**Code: 841510**	
Import & Export Air conditioning machines, comprising a motor-driven fan and elements for changing the temperature and humidity, including those machines in which the humidity cannot be separately regulated; parts thereof						
Event	Region	Trade flow	Partner Country	Net weight	Trade Value	Balance of trade
Year	Name	Im/Ex	Name	[Kg]	[USD]	+/−
2012	EU-28	Export	World	12405682	197.3 million	−
2012	EU-28	Import	World	122725218	1.1 billion	
2013	EU-28	Export	World	12474254	207.9 million	−
2013	EU-28	Import	World	100507624	1.0 billion	
2014	EU-28	Export	World	10036567	179.6 million	−
2014	EU-28	Import	World	109600482	1.1 billion	
2015	EU-28	Export	World	9072080	136.8 million	−
2015	EU-28	Import	World	104823420	900.9 million	
2016	EU-28	Export	World	9357462	144.3 million	−
2016	EU-28	Import	World	178975249	1.4 billion	

(*continued on next page*)

Table A3 (*continued*)

Source [41]:		Turbine			Code: 840682	
Import & Export Steam turbines & oth. vapour turbines (excl. for marine propulsion), of an output not exceeding 40 MW						
Event	Region	Trade flow	Partner Country	Net weight	Trade Value	Balance of trade
Year	Name	Im/Ex	Name	[Kg]	[USD]	+/−
2017	EU-28	Export	World	10425843	164.4 million	−
2017	EU-28	Import	World	188825745	1.5 billion	
Source: [41]		**Electrical Submersible Pump**			**Code: 841370**	
Import & Export Centrifugal pumps nes						
Event	Region	Trade flow	Partner Country	Net weight	Trade Value	Balance of trade
Year	Name	Im/Ex	Name	[Kg]	[USD]	+/−
2012	EU-28	Export	World	161951726	3.9 billion	+
2012	EU-28	Import	World	53104189	569.2 million	
2013	EU-28	Export	World	172214735	4.2 billion	+
2013	EU-28	Import	World	71412043	587.4 million	
2014	EU-28	Export	World	158750181	3.9 billion	+
2014	EU-28	Import	World	79621813	644.8 million	
2015	EU-28	Export	World	162094287	3.4 billion	+
2015	EU-28	Import	World	83646027	602.2 million	
2016	EU-28	Export	World	154185916	3.1 billion	+
2016	EU-28	Import	World	91673602	664.2 million	
2017	EU-28	Export	World	165249189	700.3 million	+
2017	EU-28	Import	World	99002165	3.1 billion	

Appendix F

Table A4
Time series data for Table 6

Month	Oil price			Drilling rigs world [45]				Drilling rigs Europe [45]				Geothermal drilling rigs world [45]					Geothermal drilling rigs Europe [45]				
	Cushing, OK WTI Spot Price ($/Barrel) [46]	Europe Brent Spot Price ($/Barrel) [45]	Average Oil Price ($/Barrel)	Oil	Gas	Misc*	Total	Oil	Gas	Misc*	Total	Land	Offshore	Total World	Fraction Land of total	Total **	Land	Offshore	Total Europe	Fraction Land of total	Total***
1–14	94,62	108,12	101,37	1034	251	40	1325	77	29	20	126	1023	302	1325	0,77	31	87	39	126	0,69	14
2–14	100,82	108,90	104,86	1055	246	40	1341	82	30	20	132	1023	318	1341	0,76	31	91	41	132	0,69	14
3–14	100,80	107,48	104,14	1061	242	42	1345	89	37	22	148	1011	334	1345	0,75	32	93	55	148	0,63	14
4–14	102,07	107,76	104,92	1057	251	41	1349	91	38	22	151	1020	329	1349	0,76	31	93	58	151	0,62	14
5–14	102,18	109,54	105,86	1065	250	35	1350	95	34	20	149	1024	326	1350	0,76	27	93	56	149	0,62	12
6–14	105,79	111,80	108,80	1050	257	37	1344	89	38	20	147	1024	320	1344	0,76	28	99	48	147	0,67	13
7–14	103,59	106,77	105,18	1080	264	38	1382	90	42	21	153	1046	336	1382	0,76	29	98	55	153	0,64	13
8–14	96,54	101,61	99,08	1046	251	42	1339	85	37	21	143	1024	315	1339	0,76	32	98	45	143	0,69	14
9–14	93,21	97,09	95,15	1035	248	40	1323	91	37	20	148	990	333	1323	0,75	30	98	50	148	0,66	13
10–14	84,40	87,43	85,92	1034	237	37	1308	96	34	18	148	985	323	1308	0,75	28	99	49	148	0,67	12
11–14	75,79	79,44	77,62	1049	240	35	1324	96	35	18	149	983	341	1324	0,74	26	97	52	149	0,65	12
12–14	59,29	62,34	60,82	1036	243	34	1313	95	34	19	148	979	334	1313	0,75	25	97	51	148	0,66	12
1–15	47,22	47,76	47,49	982	244	32	1258	80	30	18	128	944	314	1258	0,75	24	83	45	128	0,65	12
2–15	50,58	58,10	54,34	982	227	66	1275	85	26	22	133	951	324	1275	0,75	49	77	56	133	0,58	13
3–15	47,82	55,89	51,86	976	239	36	1251	83	30	22	135	935	316	1251	0,75	27	80	55	135	0,59	13
4–15	54,45	59,52	56,99	930	232	40	1202	65	30	24	119	902	300	1202	0,75	30	73	46	119	0,61	15
5–15	59,27	64,08	61,68	889	229	40	1158	62	30	24	116	874	284	1158	0,75	30	68	48	116	0,59	14
6–15	59,82	61,48	60,65	872	232	42	1146	62	26	25	113	869	277	1146	0,76	32	65	48	113	0,58	14
7–15	50,90	56,56	53,73	849	227	42	1118	60	24	24	108	854	264	1118	0,76	32	60	48	108	0,56	13
8–15	42,87	46,52	44,70	866	223	48	1137	57	25	27	109	867	270	1137	0,76	37	65	44	109	0,60	16
9–15	45,48	47,62	46,55	871	225	44	1140	60	24	25	109	872	268	1140	0,76	34	62	47	109	0,57	14
10–15	46,22	48,43	47,33	854	213	44	1111	60	22	26	108	841	270	1111	0,76	33	65	43	108	0,60	16
11–15	42,44	44,27	43,36	839	223	47	1109	55	22	31	108	850	259	1109	0,77	36	71	37	108	0,66	20
12–15	37,19	38,01	37,60	812	231	52	1095	58	24	32	114	845	250	1095	0,77	40	79	35	114	0,69	22
1–16	31,68	30,70	31,19	772	224	49	1045	54	24	30	108	803	242	1045	0,77	38	73	35	108	0,68	20
2–16	30,32	32,18	31,25	744	223	51	1018	50	24	33	107	793	225	1018	0,78	40	71	36	107	0,66	22
3–16	37,55	38,21	37,88	719	218	48	985	52	17	27	96	774	211	985	0,79	38	58	38	96	0,60	16
4–16	40,75	41,58	41,17	699	199	48	946	50	13	27	90	726	220	946	0,77	37	54	36	90	0,60	16
5–16	46,71	46,74	46,73	704	197	54	955	51	11	33	95	726	229	955	0,76	41	53	42	95	0,56	18
6–16	48,76	48,25	48,51	677	197	53	927	48	11	32	91	704	223	927	0,76	40	52	39	91	0,57	18
7–16	44,65	44,95	44,80	680	201	57	938	49	12	33	94	712	226	938	0,76	43	52	42	94	0,55	18
8–16	44,72	45,84	45,28	678	202	57	937	44	17	35	96	709	228	937	0,76	43	58	38	96	0,60	21
9–16	45,18	46,57	45,88	684	194	56	934	41	18	33	92	713	221	934	0,76	43	56	36	92	0,61	20

Table A4 (*continued*)

Month	Oil price			Drilling rigs world [45]				Drilling rigs Europe [45]				Geothermal drilling rigs world [45]					Geothermal drilling rigs Europe [45]				
	Cushing, OK WTI Spot Price ($/Barrel) [46]	Europe Brent Spot Price ($/Barrel) [45]	Average Oil Price ($/Barrel)	Oil	Gas	Misc*	Total	Oil	Gas	Misc*	Total	Land	Offshore	Total World	Fraction Land of total	Total **	Land	Offshore	Total Europe	Fraction Land of total	Total***
10–16	49,78	49,52	49,65	666	199	55	920	33	20	34	87	720	200	920	0,78	43	63	24	87	0,72	25
11–16	45,66	44,73	45,20	681	193	51	925	44	19	34	97	714	211	925	0,77	39	64	33	97	0,66	22
12–16	51,97	53,29	52,63	686	192	51	929	49	16	34	99	719	210	929	0,77	39	64	35	99	0,65	22
1–17	52,50	54,58	53,54	672	201	60	933	41	20	37	98	727	206	933	0,78	47	67	31	98	0,68	25
2–17	53,47	54,87	54,17	695	194	52	941	54	23	30	107	741	200	941	0,79	41	69	38	107	0,64	19
3–17	49,33	51,59	50,46	709	190	44	943	51	19	24	94	746	197	943	0,79	35	63	31	94	0,67	16

(* Misc: Miscellaneous, Baker Hughes has issued rotary rig counts and provides monthly rig counts for Oil, Gas and Miscellaneous drilling; ** As the Baker Hughes dataset did not provide data on geothermal drilling rigs specifically, The possible number of geothermal rig worldwide has been created by multiplying the fraction 'Land' by the number of rigs in the miscellaneous category; ***similar method has been applied in calculating geothermal rig number in Europe).

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