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Scenarios for geothermal energy deployment in Europe

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ABSTRACT

The use of geothermal energy in Europe is expected to grow rapidly over the next decades, since this energy resource is generally abundant, ubiquitous, versatile, low-carbon, and non-intermittent. We have expanded and adapted the integrated assessment model TIAM-ECN to more adequately reflect geothermal energy potentials and to better represent the various sectors in which geothermal energy could possibly be used. With the updated version of TIAM-ECN, we quantify how large the share of geothermal energy in Europe could grow until 2050, and analyze how this expansion could be stimulated by climate policy and technological progress. We investigate geothermal energy's two main applications: power and heat production. For the former, we project an increase to around 100–210 TWh/yr in 2050, depending on assumptions regarding climate ambition and cost reductions for enhanced geothermal resource systems. For the latter, with applications in residential, commercial, industrial, and agricultural sectors, we anticipate under the same assumptions a rise to about 880–1050 TWh/yr in 2050. We estimate that by the middle of the century geothermal energy plants could contribute approximately 4–7% to European electricity generation. We foresee a European geothermal energy investment market (supply plus demand side) possibly worth about 160–210 billion US$/yr by mid-century.

1. Introduction

Geothermal energy is increasingly seen as an option that could assist in reaching the goal of the Paris Agreement to limit the atmospheric temperature increase to 2 °C or less [1]. The European Union pays special attention to this energy resource in this respect, as attested by the €90 million worth of funds granted for R&D on geothermal technology between 2014 and 2018 within the Horizon 2020 Framework Programme alone [2]. In this article we investigate to what extent geothermal energy could contribute to the European energy mix by the middle of the century and thereby play a role in achieving the European Commission's Green Deal [2].

We recently enhanced the global energy system model TIAM-ECN, member of the family of Integrated Assessment Models (IAMs) used for instance by the Intergovernmental Panel on Climate Change [3], to better represent several geothermal energy options. As explained in [4], we updated the techno-economic characterization of geothermal energy in TIAM-ECN for power generation and the supply of district heating and cooling in the residential and commercial sectors. We found that the global level of geothermal electricity and heat generation could reach some 800–1300 and 3300–3800 TWh/yr, respectively, by 2050, depending on the climate change mitigation ambition and the future costs of Enhanced Geothermal Systems (EGS).

For the present paper we have implemented several additional upgrades to our model, notably by improving the representation of geothermal energy processes in the agricultural and industrial sectors. With a special focus on Europe, we have also fundamentally updated our estimates of application-specific long-term economic geothermal energy potentials, based on subsurface temperature data from the model developed by Limberger et al. [5]. This has been a critical improvement of our model, since the previous version of TIAM-ECN represented these potentials in only a rudimentary fashion. In three essential ways the results reported in this paper therefore constitute a novel contribution to the literature: along the dimensions of (i) geothermal potentials, (ii) their sectoral

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application and (iii) their geographical focus.

In section 2 of this article we describe our methodology in terms of (1) the model we use, (2) the technologies we simulate and (3) the scenarios we run. In section 3 we summarize our findings with regard to the levels of geothermal electricity and heat generated in Europe until 2050, the share of geothermal energy in European power supply, and the required annual supply plus demand side geothermal energy investments. In section 4 we draw our conclusions and formulate several recommendations for project developers, policy makers, and analysts. We also elaborate on subjects that we think deserve further research, for example (but not only) with IAMs.

2. Methodology

We use for our analysis the well-established IAM called TIAM-ECN (the TIMES IAM operated at TNO Energy Transition, formerly called ECN). TIAM-ECN is an energy-economy-environment model that can be employed for finding cost-minimal energy systems, at a global level as well as in several regions or countries around of the world. In this paper we only describe those elements of the TIAM-ECN model that, since our 2019 article, were modified in order to better represent geothermal energy applications [4]. For a detailed description of TIAM-ECN we refer the reader to our prior publications (see e.g. Ref. [6–9]).

2.1. Geothermal energy resources

We estimate geothermal resource potentials by building on the subsurface temperature data presented in [5]. We follow a generalized volumetric methodology based on [5,10] to estimate long-term application-specific economic potentials that are suitable as input for TIAM-ECN.

Limberger et al. [5] provide subsurface temperature data for Europe on a spatial grid of 10 km by 10 km raster cells, down to a depth of 10 km with 1 km resolution vertically. From these data we determine the total heat in place (HIP) by calculating the amount of heat, δH_z, contained in a cell of volume $\delta V_z = A\ \delta z$, located at depth z in the subsurface, in which A is the surface area of the cell and δz its height (assumed to be small in comparison to the depth z). We use the following formula, adapted from [5,10], for the local HIP:

$$\delta H_z = \delta V_z \times (\phi \rho_w C_w + (1-\phi)\rho_r C_r) \times (T_z - T_s) \tag{1a}$$

$$= A \delta z \gamma (T_z - T_s) \tag{1b}$$

In these equations, ρ_r, C_r and φ represent, respectively, the density, heat capacity and porosity of the rock. ρ_w and C_w are the water density and heat capacity, respectively. T_z is the temperature at depth z and T_s the average surface temperature. The bulk heat capacity γ varies along with the density, heat capacity and porosity of the reservoir under consideration. The values we use for these parameters are summarized in the appendix, and yield $\gamma = 2.81$ PJ km^{-3} K^{-1}. By integrating the above equation over a depth of 10 km, we obtain overall HIP values for Europe on a 10 by 10 km raster grid. These represent the theoretical amount of heat that can be extracted from the subsurface over the entire geological column down to a depth of 10 km.

In practice, however, the available HIP for any given geothermal application is much lower than the theoretical upper limit determined by the above equations. There are three main factors that define whether the HIP at a given location can be used in any geothermal application: the surface temperature T_s, the formation temperature T_z, and an application-dependent minimum for the required temperature difference ΔT. Table 1 summarizes the values of these three parameters (with a minimum and maximum, if applicable) for all geothermal applications considered in our model. For each application, if the surface temperature of a raster cell falls outside the boundaries given in Table 1, the HIP in the column under the cell becomes zero (that is, the application is unavailable). For any geothermal application the HIP will only be non-zero from below the depth at which the difference between the formation temperature T_z and the surface temperature T_s exceeds the minimum temperature difference ΔT (if any such depth exists).

After applying the constraints listed in Table 1, we scale down the resulting application-specific HIP values in order to achieve realistic estimates for the technical application-specific geothermal energy potentials. We therefore multiply the HIP values with the ultimate recovery factor (UR), which expresses the effect of limitations on the available land area and on the efficiency of thermal exchange between rocks and fluids (see e.g. Ref. [11]). In the present study we adopt a definition of UR that also includes an estimate of economic limitations by setting UR = 0.1%, in line with the effective UR reported in [5]. This value reflects that in practice, even for well-established conventional geothermal technologies, only a small part of the subsurface can be effectively exploited (for an example in the Netherlands, see Refs. [12,18]). Because of the relevance of the UR factor for the effective geothermal energy exploitation potential, we have varied its central value of 0.1% down to 0.01% and up to 1% by way of sensitivity test in order to inspect the robustness of our findings (see the Conclusions section of this paper).

Fig. 1 presents the economic potentials for geothermal energy applications in Europe at three different depth ranges, obtained by calculating the HIP, applying the constraints listed in Table 1 and multiplying with an effective UR of 0.1%. These potentials can be fed into TIAM-ECN (or other similar energy system models or IAMs), which allows one to compute, under specific scenario assumptions, the deployment levels of the corresponding geothermal energy applications. The uniqueness and novelty of this approach is that it enables determining the competitiveness of geothermal applications with respect to other technologies available in the energy system. By us this is done in a dynamic way, as opposed to the static manner employed by Limberger et al. [5], since the costs of all energy technologies in an IAM like TIAM-ECN vary. Indeed, these costs typically decrease over time, especially for renewable energy alternatives, either exogenously or through learning phenomena. Constraints are included in our model to make sure that the potentials are mutually exclusive: in other words, if a certain application is deployed, the corresponding share of the potential it utilizes is no longer available for other applications.

Fig. 1 shows that, with the exception of Iceland and a few other regions that display volcanic activity, the potential for geothermal power generation is limited to reservoirs at depths below 2 km. In contrast, direct geothermal heat applications in agriculture, industry and the built environment can already be realized from reservoirs at depths of less than 2 km; for agriculture this is even the case for shallow depths of less than 200 m. Space cooling applications are only possible in the south of Spain, Italy, Greece and Turkey, since only in those parts of Europe minimum average surface temperatures are above 15 °C. Cooling applications in these countries typically require geothermal resources at depths below 2 km.

2.2. Geothermal energy options

The original TIAM model includes only a limited number of rather stylized geothermal energy technologies. For the purpose of our previous study we expanded and improved their representation in TIAM-ECN for both the power sector and the residential and

Table 1
Application-dependent parameters, from Limberger et al.[5,10].

Category	Application	min T_s [°C]	max T_s [°C]	min T_z [°C]	min ΔT [°C]
Direct use	Space and water heating	−15	15	70	40
Direct use	Space cooling	15	–	70	35
Direct use	Agriculture	−15	15	45	25
Direct use	Industry	–	–	70	40
Electricity	Power sector	–	–	–	80

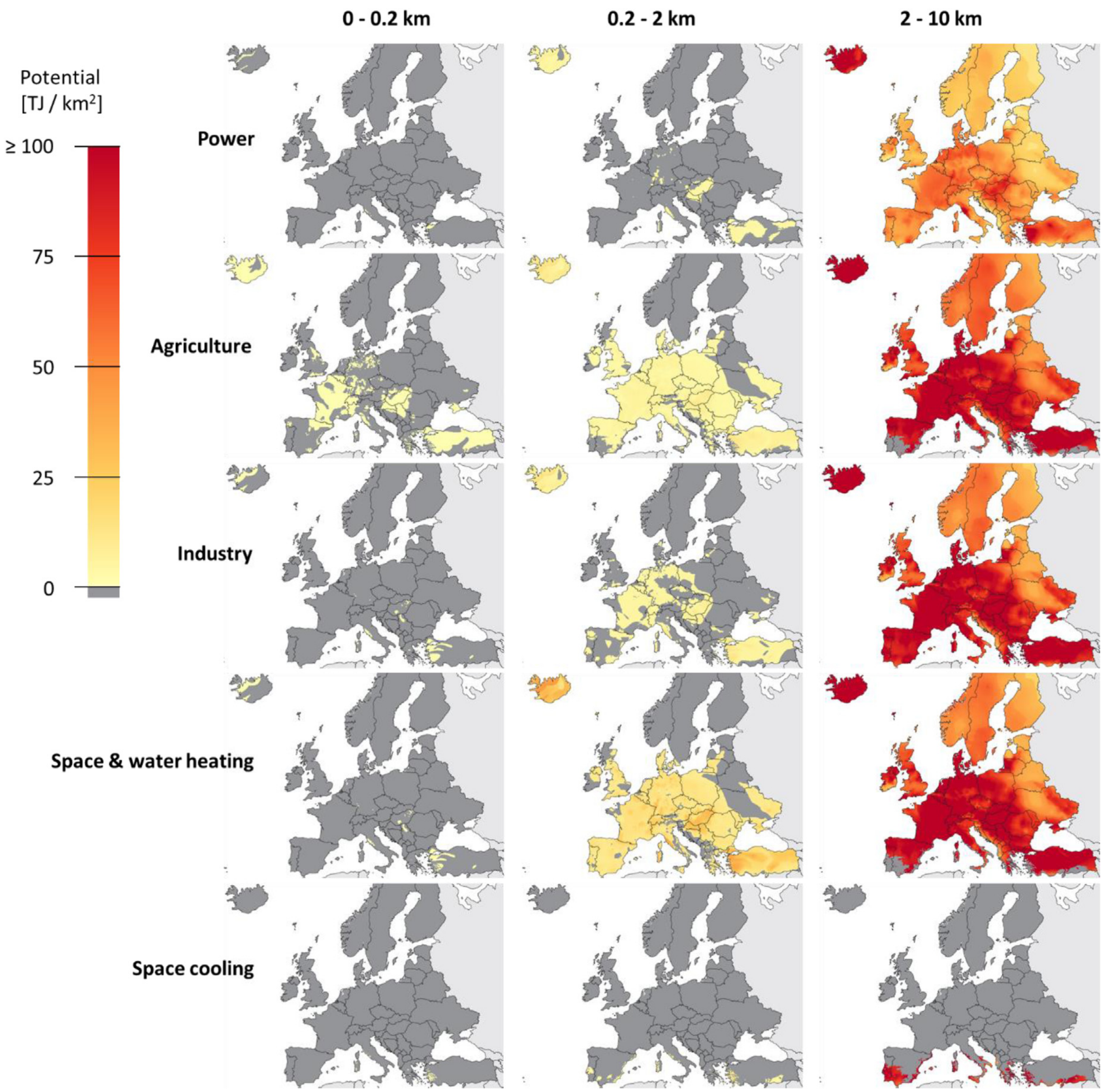

Fig. 1. Long-term economic potentials for various geothermal applications in Europe at three different depth ranges.

commercial sectors, which allowed us to better project the prospects for geothermal energy into the future. In the latest version of TIAM-ECN used for the present paper, we have further refined the set of geothermal energy options, notably in industry and the agricultural sector, for which we have updated both their costs and main technical characteristics. For a detailed description of our previous updates in the power, residential and commercial sectors, we refer to [4]. We here report on the way in which we have refined the representation of geothermal energy use in industry and the agricultural sector.

Table 2 depicts the capital costs (in M$/PJ/yr) for the multiple geothermal energy options that we introduced in TIAM-ECN for agriculture and industry. The main purpose of geothermal energy use in agriculture is to provide heat for greenhouses in horticulture. We model a single geothermal process for agriculture in TIAM-ECN, based on either conventional or EGS technology. The capital cost (CAPEX) of this application is based on that for geothermal space heating in the commercial sector (see Ref. [4]) plus a mark-up to account for technical adaptations necessary to match the specific requirements for greenhouse heating. In industry, geothermal

Table 2
Geothermal energy capital costs in industry and agriculture.

Technology	Sector	CAPEX [M$/PJ/yr]	
		2010	2050
Direct use conventional	Agriculture	96	82
Direct use EGS	Agriculture	144	122
Steam and process heat conventional	Chemicals	41–124	41–124
Steam and process heat EGS	Chemicals	61–187	61–187
Steam and process heat conventional	Iron and steel	51–145	51–145
Steam and process heat EGS	Iron and steel	77–218	77–218
Steam and process heat conventional	Pulp and paper	41–118	41–118
Steam and process heat EGS	Pulp and paper	61–177	61–177
Steam and process heat conventional	Non-ferrous metals	41–124	41–124
Steam and process heat EGS	Non-ferrous metals	61–187	61–187
Steam and process heat conventional	Non-metals	41–150	41–150
Steam and process heat EGS	Non-metals	61–225	61–225
Steam and process heat conventional	Other industries	41–124	41–124
Steam and process heat EGS	Other industries	61–187	61–187

energy can be employed to supply direct heat or steam for processes such as drying, evaporation and pasteurization (see e.g. Ref. [13,14]). These processes require heat or steam at temperatures between typically 50 and 300 °C. They can be implemented in notably food processing, chemicals production, materials mining and processing, as well as in the production of paper and textile goods. As detailed in Table 2, these applications have been mapped into the existing industrial subsectors in TIAM-ECN. Technologies for which no specific subsector is available in TIAM-ECN have been grouped under the generic category “other industries”. The costs of geothermal energy technologies in industry are based on a stylistic commercial water heating process (see Ref. [4]) minus the costs of distribution through district heating infrastructure plus, where applicable, a mark-up for technology-specific adaptations and a temperature-dependent mark-up or -down. Conventional and EGS technologies for the different industrial subsectors are modelled as three separate applications: a low- and high-cost process heat option plus a single steam usage option. The corresponding capital costs are specified as ranges in Table 2. The use of geothermal electricity in industry is not modelled explicitly but (like for other sectors) is implicitly taken into account via the deployment of geothermal processes in the power sector and the electrification of the energy system in industry. As detailed in [4], conventional processes can only exploit potentials down to a depth of around 2 km, while EGS processes are required for potentials down to larger depths. We adopt CAPEX values for options based on EGS that are higher than those for conventional technologies, to reflect the additional equipment needed for hydraulic stimulation and the higher drilling costs for deeper wells.

2.3. Scenarios

An analysis with TIAM-ECN implies finding cost-minimum energy systems for a set of regions under scenario-specific constraints. Assumptions are adopted for policy measures such as for greenhouse gas (GHG) emission reduction targets, technology features like cost reductions, availability of primary energy resources and demand projections for energy services. For this paper we have developed four scenarios, summarized in Table 3, that zoom in on Western Europe.[1] The first scenario, called REF, aims at representing how the global energy system could develop in the absence of long-term climate change control policies. The second one, REF_2DC, depicts a situation in which Europe sets a stringent zero-GHG emission target for 2050, while the rest of the world stays on a trajectory that ensures, with a 70% likelihood, that the global average temperature increase remains within a maximum of 2 °C, in line with the goal of the Paris Agreement. This scenario matches the ambition expressed in the European Climate Law, which constitutes the legal basis for the objective to make Europe the first climate-neutral continent in the world by 2050 (EC, 2019). The last two scenarios, GEO and GEO_2DC, resemble REF and REF_2DC, respectively, in all aspects except for the costs of EGS technology. While in the REF and REF_2DC scenarios we assume that the costs of conventional and EGS processes decline at the same relatively conservative pace, following [4], we assume in the GEO and GEO_2DC scenarios that EGS technology costs decline with a higher learning rate of 13% between 2010 and 2050. The basis of this more optimistic cost trajectory is expressed by the learning curve observed for fracking technology applied to deep natural gas wells [15].

Table 3
Summary of scenarios for Europe.

Scenario	Geothermal technology progress	2 °C policy
REF	Conservative	No
REF_2DC	Conservative	Yes
GEO	Optimistic	No
GEO_2DC	Optimistic	Yes

3. Results

Fig. 2 shows the pathways for geothermal electricity generation in Europe under our four scenarios obtained with TIAM-ECN (see the Appendix for the corresponding electricity generation capacities). For conventional (binary and flash) geothermal energy systems the projections do not vary significantly between scenarios, while a moderate overall growth is observed during the three decades of our simulation runs. In the absence of stringent climate policy (REF and GEO scenarios), the steeper EGS cost reductions in the GEO scenario induce a significant additional uptake of this innovative technology between 2040 and 2050. In REF_2DC and GEO_2DC, EGS deployment (and to a lesser extent also that of conventional geothermal technology) is consistently higher than when the zero-GHG target is not in place, and does practically not depend on EGS learning rate assumptions. This indicates that climate policy has a higher impact on the growth of geothermal electricity generation than technology cost reductions.

In Fig. 3 we show our projections for geothermal heat production per sector in Europe under the four scenarios generated with TIAM-ECN (see Appendix for the corresponding capacities). The trends are similar to those observed in Fig. 2 for the power sector. Direct heat from geothermal energy is mostly used to provide space and water heating in the residential and commercial sectors, where it replaces predominantly natural gas. Moderate geothermal energy usage levels are found in agriculture, mainly for the purpose of greenhouse heating, while also industrial use remains small. There are several reasons for the latter, which we spell out in the Conclusions section of this article, but we reckon that our findings regarding the limited use of geothermal energy in industry may need to be subjected to more in-depth follow-up research. Generically, because of costs, only a limited number of 10-km-depth resources are used and these may not always find application in industry, since temperature requirements in this sector often exceed the 300 °C level.

[1] Western Europe is a region in TIAM-ECN that includes the following countries: Andorra; Austria; Belgium; Switzerland; Germany; Denmark; Spain; Finland; France; Faeroe Islands; Channel Islands; Isle of Man; United Kingdom; Gibraltar; Greece; Greenland; Ireland; Iceland; Italy; Liechtenstein; Luxembourg; Monaco; Malta; Netherlands; Norway; Portugal; San Marino; Sweden.

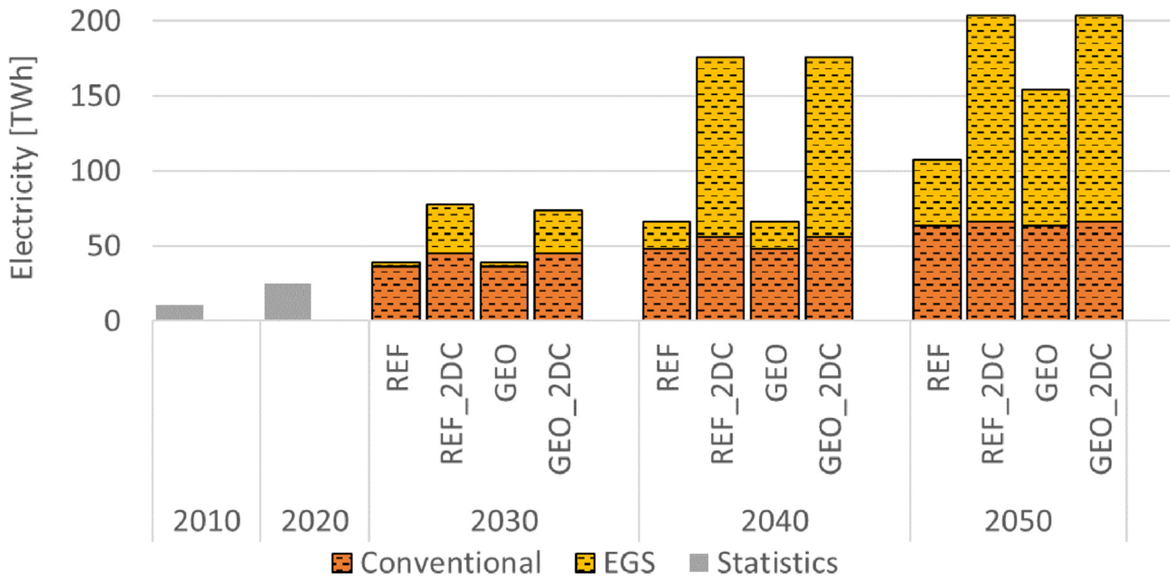

Fig. 2. Projections with TIAM-ECN for geothermal electricity generation in Europe. *Statistical data for 2010 are taken from IEA* [16]*; for 2020 they are derived from IEA* [17].

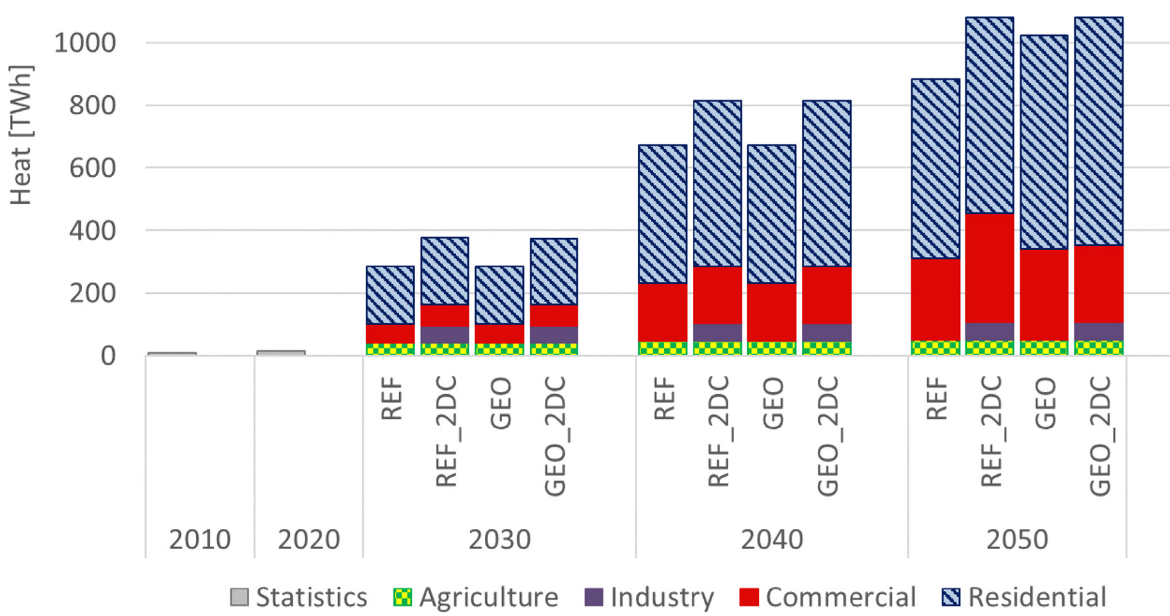

Fig. 3. Projections with TIAM-ECN for geothermal heat production in Europe. *Statistical data for 2010 and 2020 are taken, respectively derived, from Lund and Boyd (2015) and Lund et al. (2015).*

Fig. 4 depicts the evolution of technology shares in the European electricity supply mix until 2050 according to TIAM-ECN. The use of renewable energy options together with nuclear energy and carbon dioxide capture and storage (CCS) technologies, applied to both natural gas and biomass, enable the achievement of a zero-GHG emissions power sector in the two 2DC scenarios. Geothermal energy contributes between 4% and 7% to the electricity generation mix by the middle of the century, while solar PV and wind energy reach shares of, respectively, 15–20% and 6–34% around 2050, partly by displacing hydropower and CCS.

Fig. 5 plots our findings for the annual geothermal energy investment requirements in Europe, split between the different sectors in which geothermal technologies are deployed. The total market size for geothermal energy in Europe (supply plus demand side) could amount to 160–210 billion US$/yr in 2050, with the largest share of geothermal investments directed towards residences (about 70%) and commercial buildings (around 25%).

4. Conclusions

In this study we have taken the work by [5] a substantial step further. Limberger et al. [5] determine the economic potential by calculating the levelized cost of electricity (LCOE) of geothermal resources for power generation in Europe on the basis of the technical potential that they deduce from detailed information on underground temperature gradients and formation properties. They compare the resulting geothermal energy LCOE values with reference levels, at several points in time until 2050, at which they assume that competitiveness is reached with LCOE figures for incumbent technologies. Limberger et al.[5] do not account for the

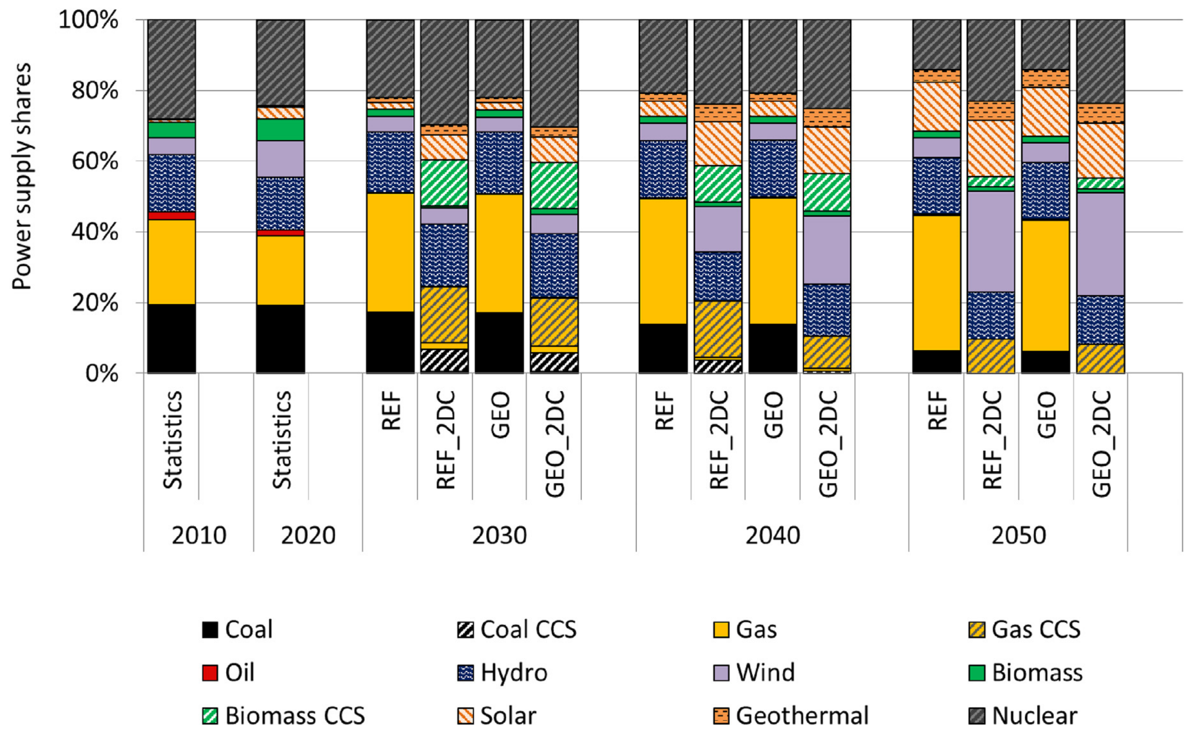

Fig. 4. Projections with TIAM-ECN for the total European electricity supply mix. *Statistical data for 2010 and 2020 are taken, respectively derived, from IEA* [17].

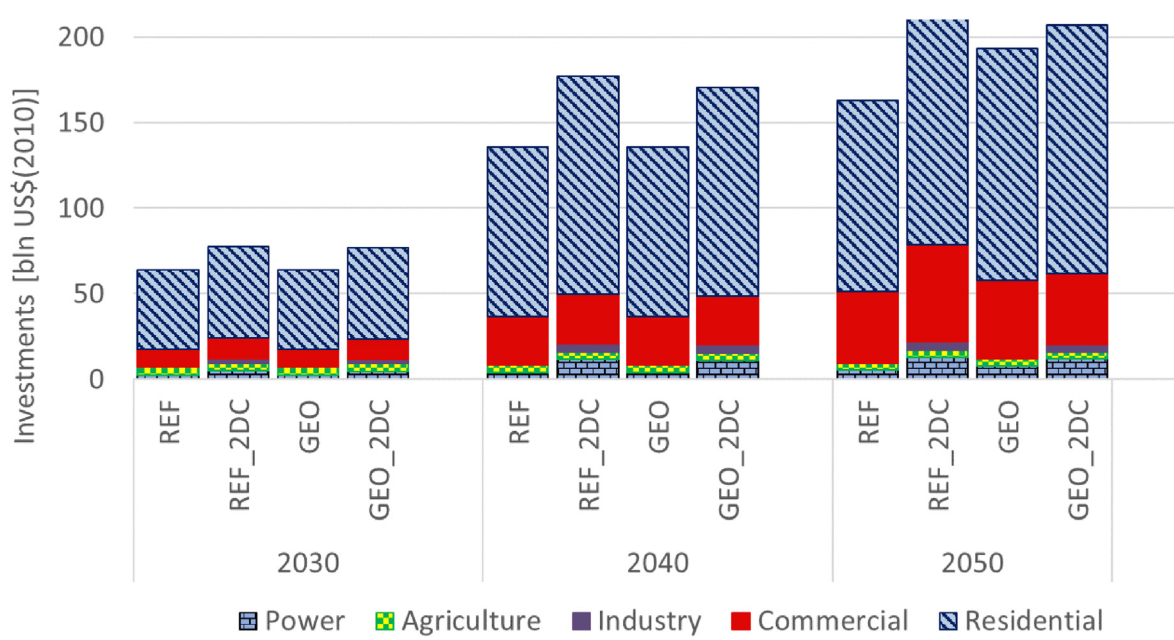

Fig. 5. Calculations with TIAM-ECN for the annual investment requirements for geothermal energy in Europe.

fact that the LCOE values for renewable and fossil-based power production options themselves are dependent on developments in multiple sectors of the economy and are thus intrinsically subject to change. In order to more closely reflect reality, we argue that one should not adopt static benchmarks for LCOE values *a priori*. We correct for this shortcoming in [5] by using the TIAM-ECN model, so as to get a better sense of what the *competitive potential*, as opposed to the *economic potential*, for geothermal energy could be.

With the TIAM-ECN model we have computed how much the use of geothermal energy in Europe could grow until 2050, and have investigated how its expansion could be stimulated by climate policy and cost reductions achieved through technological learning. We have done this for both geothermal energy's main applications: power production and the extraction of heat. For the former we foresee a level of about 100–210 TWh/yr by 2050, depending on assumptions regarding climate change mitigation ambition and technological progress for EGS. For the latter we project, under the same assumptions, a magnitude of around 880–1050 TWh/yr in

2050, mainly to provide heat in the residential and commercial sectors. We project a limited use of geothermal energy in agriculture, and a small deployment of geothermal technology in industry. The small contribution of geothermal energy to industry can mainly be explained by the large potential for electrification in this sector, as well as the extensive possibilities for the use of natural gas (with CCS in the 2DC scenarios) as heat supply option. It would be an interesting subject for future research to explore the role of geothermal energy in industry in scenarios in which the availability or usability of natural gas in Europe is limited, e.g. because of import restrictions or as a result of implementation obstacles for CCS. We estimate that by 2050 geothermal electricity plants, partly in competition with both renewable and fossil fuel based counterparts (the latter equipped with CCS in the 2DC scenarios), could contribute by approximately 4–7% to European electricity generation. We have calculated the changes in our geothermal electricity generation findings as a result of variations in multiple model input assumptions and find, on the basis of extensive sensitivity tests, that our projections are robust under changes in even the most critical parameters (see Figure A4 in the Appendix and the associated text).

Limberger et al. [5] find an economic potential for geothermal electricity generation in 2050 that exceeds 500 GW in Europe. In the present paper we obtain an aggregated capacity of at most only 30 GW for geothermal power generation in that year (see Appendix). This contrast can only partly be attributed to the lower cost assumptions for EGS processes and the somewhat broader geographical scope in [5]. Given the magnitude of the gap in deployed capacity between the two studies, we conclude that it is important to carefully select the methodology with which one attempts to determine economic or competitive resource potentials for geothermal energy – as with other energy technologies – and that it may matter significantly whether one uses a static approach (as adopted by Ref. [5]) or a dynamic method (as employed in the present study) to determine the extent to which geothermal energy can compete in future global energy systems.

The many assumptions used in estimating geothermal energy resource potentials, and the intrinsic uncertainty in subsurface temperature data and geological formation properties, can lead to wide error margins for the potentials used in static or dynamic energy systems analyses. An interesting extension of our present work would be to further investigate how the deployment of geothermal energy may vary if different sets of assumptions are used in the calculation of potentials, on global, regional, national and local levels. For example, we have determined the sensitivity of our results for geothermal power production in Europe to more pessimistic, respectively more optimistic, values of the UR parameter in the range of 0.01–1% (see Figure A4 in the Appendix). It could be worthwhile to determine the sensitivity of our results to variations in other such geothermal energy resource potential related parameters and to changes in the geographical scale at which we perform our analysis. Since the power extraction mechanism is different for distinct reservoirs, such as hydrothermal formations, hot dry rocks or supercritical calderas, we may in the future refine our simulations in this regard as well. Considering a single production mechanism, like we do at present, could over- or underestimate the geothermal resource potential. Introducing individual energy extraction processes for different reservoir types could affect the overall geothermal power generation level.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

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Appendix

In Table A1 we report the values of the main physical parameters used in Equation (1).

Table A1
Rock properties, from Limberger et al. [5,10].

Parameter	Description	Value	Unit
φ	Rock porosity	0.15	–
C_w	Water heat capacity	4250	J/(kg K)
ρ_w	Water density	1078	kg/m^3
C_r	Rock heat capacity	1000	J/(kg K)
ρ_r	Rock density	2500	kg/m^3
γ	$\varphi\rho_w C_w + (1-\varphi)\rho_r C_r$	2.81	PJ/(km^3 K)

In Fig. A1 we show a schematic representation of the geothermal energy processes that we implemented in TIAM-ECN for industry.

A rock porosity of 15% is justifiable for sedimentary basins down to about 3 km (see Ref. [10]). For deeper formations and non-sedimentary basins we assume that the corresponding potential can only be exploited through hydraulic stimulation, which could yield porosities of around 15%. In TIAM-ECN we apply this assumption by making this potential only available to EGS processes (see Ref. [4]).

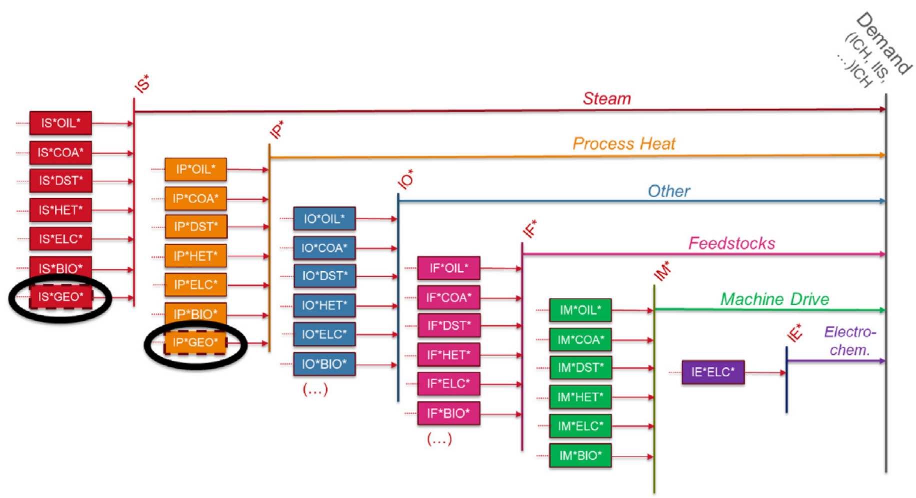

Fig. A1. Geothermal energy processes in industry represented in TIAM-ECN.

Fig. A2 shows the pathways for European geothermal electricity capacity under our four scenarios obtained with TIAM-ECN.

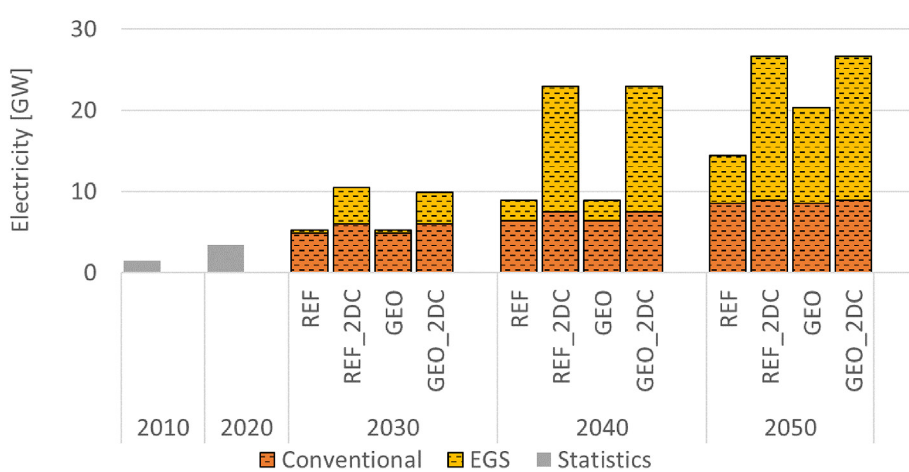

Fig. A2. Projections with TIAM-ECN for European geothermal electricity generation capacity.

Fig. A3 shows the pathways for European geothermal heat capacity under our four scenarios obtained with TIAM-ECN.

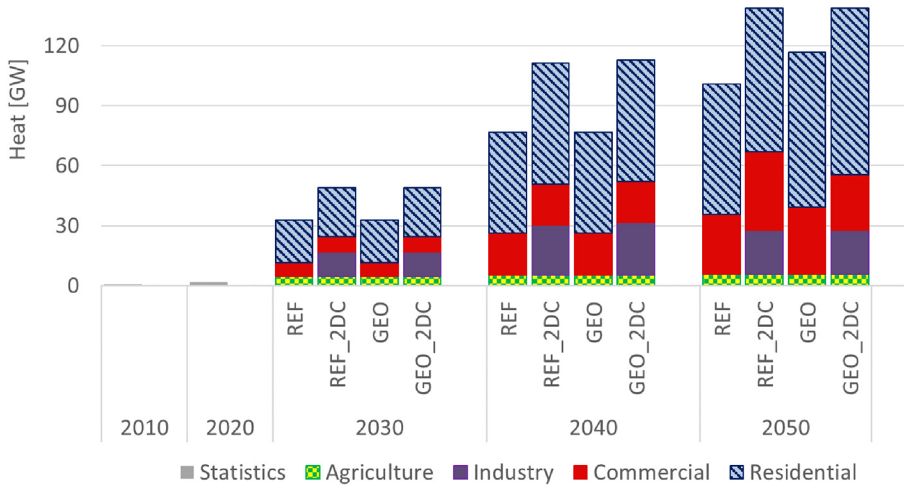

Fig. A3. Projections with TIAM-ECN for European geothermal heat production capacity.

In Fig. A4 we plot the result of our sensitivity tests regarding the model assumptions that most heavily impact our scenario runs in terms of additional geothermal power generation: whether or not to adopt stringent climate policy, the rapidity of cost reductions for generic geothermal energy technology, the rapidity of cost reductions for EGS technology, and the UR factor. We observe that whether or not the 2 °C target of the Paris Agreement is adhered to has the highest effect on the geothermal power production level, but that in all sensitivity cases the impact is modest (at most a few % in terms of overall electricity generation). As can be expected, geothermal power production increases with the stringency of climate policy and with faster geothermal energy cost reductions, and decreases with slower geothermal energy cost reductions. Decreasing the UR by as much as a factor of 10 results in a modest but consistent reduction in geothermal power production (of around 0.5 TWh), while increasing it by a factor of 10 has no significant effect on the production level (not shown).

We also did sensitivity tests for the availability of nuclear power and the costs of PV and wind energy, but changes in our assumptions regarding these facets had a negligible impact on the production of geothermal electricity, smaller than that as a result of changes in UR. Our main message is thus that our results are robust across a wide range of assumptions for other technologies in the power sector.

Author credits

F.D.L., J.D.v.W. and B.v.d.Z. designed the study; F.D.L. and B.v.d.Z. drafted the article; F.D.L., L.P.N. and J.L. gathered the data and performed the modeling work; F.D.L. generated the figures; F.D.L, L.P.N., J.L., J.D.v.W. and B.v.d.Z. analysed the data and discussed the results; F.D.L. and B.v.d.Z. produced the final manuscript.

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[1] COP-21. Paris agreement, united nations Framework convention on climate change, conference of the parties 21. Paris: France; 2015.

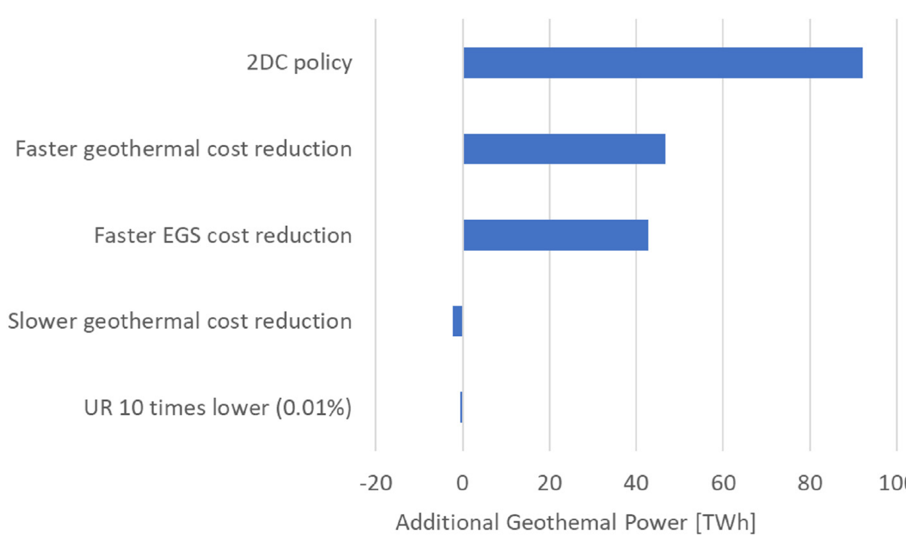

Fig. A4. Key sensitivity tests for geothermal power production in Europe in 2050 projected with TIAM-ECN.

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