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Integrated assessment projections for global geothermal energy use

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ABSTRACT

The use of geothermal energy is expected to grow rapidly over the next several decades at many places in the world, since geothermal resources are abundant, and because this renewable energy option is both a low-carbon and non-intermittent technology. With the integrated assessment model TIAM-ECN we quantify how large its growth could be until 2050, and analyze how this expansion could be stimulated by both climate policy and technological progress. We inspect both geothermal energy's main applications: the generation of electricity and the production of heat. For the former, we project an increase to a power production level of around 800–1300 TWh/yr in 2050, depending on assumptions regarding climate ambition and cost reductions for enhanced geothermal resource systems. For the latter, with an emphasis on residential and commercial heat use applications, we anticipate under the same assumptions a rise to about 3300–3800 TWh/yr in the same year. We estimate that by 2050 geothermal energy plants, partly in competition with renewables like solar and wind power, as well as with incumbent fossil fuel based power production, could contribute approximately 2–3% to global electricity generation. If all nations stay on track of the Paris Agreement target by not increasing the global average atmospheric temperature with more than 2°C, and if the costs of geothermal energy production from deep formations reduce with the same learning rate of 13% that has been empirically observed for fracking technology applied to natural gas fields, we project a possible total geothermal energy investment market (supply plus demand side) worth about 500 billion US\$/yr by mid-century.

1. Introduction

Geothermal energy is gaining strong interest from both the private and public sector. Analysts expect that its use will grow rapidly over the next several decades at many places in the world (IEA, 2011; REN21, 2018). Among the multiple reasons for the optimistic prospects for this well-established technology are that geothermal energy resources are abundant, and that their global potential is increasing as a result of recent technological progress that has made geothermal formations accessible at greater depths thanks to processes like hydraulic fracturing (fracking). Geothermal energy is also in principle a low-carbon renewable technology that can contribute to reaching the ambition of the Paris Agreement to limit the global average atmospheric temperature increase to no more – preferably less – than 2°C (ESMAP, 2012; COP-21, 2015). As opposed to intermittent low-carbon options like solar photovoltaics (PV) and wind power, geothermal energy has as additional benefit that it is a non-intermittent alternative, i.e. it is available also “when the sun doesn’t shine or the wind doesn’t blow”. Geothermal energy can deliver baseload services, but may also play a

‘flexibility’ role in future sustainable electricity systems.

The necessity to achieve net zero global CO₂ emissions by 2050 in order to achieve the target of the Paris Agreement stimulates the use of low-carbon energy technologies, including geothermal energy (IPCC, 2018). While in the 20th century geothermal energy use was mainly practiced in areas with near sub-surface heat availability, such as at places with volcanic activity, over the past few decades the possibility of drilling to depths of several kilometers has allowed for its potential usage in many regions of the world. Developed countries are prime candidates for geothermal energy production because of their financial means, their technological advancement, and the availability of required knowledge and expertise. Geothermal energy can also be of great use in parts of the developing world, where it can serve implementing “Sustainable Energy for All” programs (UN, 2012) and fulfilling “Sustainable Development Goals” (SDGs: notably no.7 “affordable and clean energy” and no.13 “climate action”; see SDG, 2015). An example is Kenya, whose government actively pursues the development of geothermal energy, as it can be instrumental in both stimulating economic growth and meeting low-emission goals (see e.g.

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Dalla Longa and van der Zwaan, 2017).

All major publications on the global energy transformation foresee an essential role played by renewable technologies, and many studies consider geothermal energy as one of the promising renewable newcomers (see, for example, MIT, 2006; IEA-WEO, 2018; IEA-ETP, 2018; IRENA, 2018). The global installed capacity of geothermal electricity generation reached a level of slightly above 10 GW in 2010, while for more established renewable technologies like PV and wind power the level today amounts to about 500 GW each (REN21, 2018). Present technology developments are such that installed geothermal power production capacity could well exceed the 100 GW level by 2050. This prospect motivated us to undertake the present study, inspect possible scenarios for geothermal energy deployment under different economic and climate policy conditions, and quantify its possible contribution to the global energy system by the middle of the century.

Integrated assessment models (IAMs) are energy-economy-environment models that can help in designing alternative energy transition and decarbonisation pathways, both globally and for individual regions or countries. They have extensively been used in the multiple reports published by the Intergovernmental Panel on Climate Change (IPCC) and have served to inform both national policy makers and international climate negotiators (IPCC, 2011, 2014). IAMs have thus far hardly been used for analyses on the global potential of geothermal energy. In this paper we aim to bridge this gap in the literature. While many studies have been undertaken on the technical and/or economic resource potential of geothermal energy for various parts of the world (see e.g. Kramers et al., 2012; van Wees et al., 2012; Limberger et al., 2014; Trumpy et al., 2016; Limberger et al., 2018), little attention has been paid to date to studying how geothermal energy behaves in a broader energy system perspective. Among the few exceptions are van Wees et al. (2012); Limberger et al. (2014), and Trumpy et al. (2016), who in addition to calculating technical geothermal energy potentials – for the Netherlands, Europe, and Italy, respectively – determine economic potentials by calculating the costs of geothermal electricity and compare these with fixed cut-off levels. The drawback of the work in these three studies, however, is that their method is static and does not reflect the complex interactions between multiple energy technologies in different sectors. Our aim is to inspect the competitiveness of geothermal energy in a dynamic energy system that covers all main elements of the energy economy, for which we use TIAM-ECN, a well-known global IAM.

In Section 2 of this article we describe our methodology in terms of, respectively, (1) the model we use, (2) the technologies we simulate, and (3) the scenarios we run. In Section 3 we summarize our findings in terms of the amounts of geothermal electricity and heat generated until 2050, the share of geothermal energy in global 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 (IAM) analysts.

2. Methodology

2.1. TIAM-ECN

We use for our analysis the well-established integrated assessment model TIAM-ECN (the TIMES Integrated Assessment Model operated at ECN part of TNO), which is an energy-economy-environment model that can be employed for finding cost-minimal energy systems. Since TIAM-ECN covers all main sectors (electricity generation, industry, residences and commerce, transport), the model has been used for the analysis of subjects in several domains, including transport (see Rösler et al., 2014), power supply (Keppo and van der Zwaan, 2012; Kober et al., 2016), and burden-sharing among countries for global climate change control (Kober et al., 2014). Other examples of studies with TIAM-ECN include work on global and regional technology diffusion

(see for instance van der Zwaan et al., 2013, 2016). We refer to these publications for detailed descriptions of the multiple parts of the TIAM-ECN model and restrict ourselves to listing its main features here.

TIAM-ECN is a version of the well-established TIAM model developed in the context of the IEA Implementing Agreement IEA-ETSAP, the Energy Technology Systems Analysis Program of the International Energy Agency (the energy analysis branch of the Organization for Economic Cooperation and Development (OECD) in Paris). TIAM is a member of the family of technology-rich energy systems models based on the TIMES model generator and is described in detail in Loulou and Labriet (2008) and Loulou (2008). As bottom-up model it is characterized by achieving a partial equilibrium in which energy production meets an essentially exogenously determined demand for energy services. TIAM is a linear optimization model simulating the development of the global energy economy from resource extraction to final energy use over a period of over 100 years. Its regional disaggregation separates the world in a number of distinct geographical areas, 15 in its original format and refined to 20, then 36, over the past years for TIAM-ECN (see Kober et al., 2016; van der Zwaan et al., 2018). The objective function of TIAM-ECN consists of the total discounted aggregated energy system costs calculated over the full time horizon summed across all 36 regions. Running scenarios with TIAM-ECN involves minimizing this objective function.

The main cost components included in the objective function are investment costs, fuel costs and fixed plus variable operation and maintenance (O&M) costs. Other cost components such as decommissioning and infrastructure costs are also included, albeit in a simplified way. The partial equilibrium approach of TIAM-ECN implies that demand for energy services responds to changes in their respective prices through end-use price elasticities. Savings of energy demand and corresponding cost variations are thus accounted for in the objective function. The database associated with TIAM-ECN includes hundreds of technologies for a broad set of different sectors: for a general description of the reference energy system of TIAM-ECN see Syri et al. (2008).

2.2. Geothermal energy representation

The original TIAM model includes a limited number of rather stylized geothermal energy technologies. For the purpose of this study we have expanded and improved their representation in TIAM-ECN, which allows us to better project the prospects for geothermal energy into the future. In the new version of TIAM-ECN we have refined the set of geothermal energy options and updated their system costs and main technical characteristics for both the power sector and the residential and commercial sector. Although we expect great opportunities for geothermal energy in the form of direct process heat usage in industry and agriculture in the medium to long term – in some countries deep underground heat use is already common practice in, for instance, greenhouses – for the moment we do not yet distinguish between the multiple possibilities in these two sectors in TIAM-ECN. In the power sector we represent both flash and binary plants (ESMAP, 2012), as well as electricity generation devices based on enhanced geothermal systems (EGS) that rely on deep geothermal resources obtained through fracking technology.¹ In the residential and commercial sector we represent heat pumps for ambient heating and cooling relying on shallow underground geothermal resources, direct heat usage for water heating and ambient heating and cooling, and direct heat usage for these purposes from EGS.

Table 1 lists our central assumptions for the costs of geothermal

¹ Flash plants separate high temperature steam (> 180°C) directly from geothermal reservoir fluids, after which it is piped to a turbine to generate electricity. In binary plants heat (> 70°C and < 180°C) is recovered from the geothermal fluid to vaporize a fluid with low boiling point that drives a turbine. EGS use hydraulic fracturing ('fracking') techniques to increase the permeability and allow for heat recovery from (ultra) deep formations.

Table 1
Geothermal power capital costs.

Technology	CAPEX [\$/kW]				
	2010	2020	2030	2040	2050
Flash	4000	3800	3420	3249	3087
Binary	6000	3900	3510	3335	3168
EGS (existing)	8000	5200	3640	3494	3372
EGS (future, low cost)	10400	6760	4732	4543	4384
EGS (future, med cost)	12000	7800	5460	5242	5058
EGS (future, high cost)	14400	9360	6552	6290	6070

power capacity (CAPEX, in \$/kW)² for the six options simulated in TIAM-ECN: two conventional ones (flash and binary) and four EGS based ones with progressively higher costs. The numbers are based on IEA (2011), but updated to reflect recent market trends. All six technologies are assumed to reduce their costs until 2050, especially the EGS based options. We assume that fixed operation and maintenance (O & M) costs amount to 2–4% of the costs of geothermal power capacity, and that variable O&M costs are negligible.

The CAPEX numbers in Table 1 include all necessary drilling and surface plant costs, but do not account for the costs associated with exploration. By omitting the exploration phase we exclude the costs associated with e.g. seismic mapping and test-well drilling, which like in the oil and gas industry customarily precede the production phase. We indirectly represent the costs incurred during the exploration phase to some extent, however, by choosing a cost of capital (WACC, or weighted average cost of capital) for geothermal energy that is higher than that for other renewable energy technologies. The higher WACC reflects the risks associated with geothermal energy at the front end of the cycle – that is, before production takes place – as expressed by the hit-and-miss ratio of geothermal well exploration.

In Table 2 we show the capital costs for the two types (commercial and residential, respectively) of ground source heat pumps that we introduced in TIAM-ECN (in M\$/PJ/yr). These heat pumps provide heating in autumn and winter, cooling in spring and summer, are specified with seasonal availability factors, and consume electricity. Cost data are in principle based on IEA (2011), but have been aligned with those in the recently updated OPERA model database (van Stralen et al., 2018). Since heat pumps are relatively mature technologies, we assume modest cost reductions until 2050. Costs in the commercial sector are substantially lower than in the residential sector thanks to economies-of-scale.

Table 3 depicts the capital costs for the multiple direct use options for geothermal energy that we introduced in TIAM-ECN (in M\$/PJ/yr). We distinguish between two technologies (conventional and EGS), two types of heating (ambient/space and water), and two applications (residential and commercial). The representation of all eight options has been improved to reflect the fact that they consume non-negligible amounts of electricity. Where possible cost data are based on IEA (2011), but have otherwise been synchronised with those in the OPERA model database (van Stralen et al., 2018). A mark-up of 74 M\$/PJ/yr has been used to account for district heating infrastructure costs (IEA-ETSAP, 2013). Capital costs for EGS are assumed to be 50% higher than for conventional systems in 2010, and we assume steeper cost reductions for EGS based technology than for conventional alternatives, such as in the power sector. We assume that fixed O&M costs for heat pumps and direct heat use technologies are negligible, and variable O&M costs equal the costs of the electricity used to drive these systems.

The topology structure with which we model geothermal energy in TIAM-ECN involves three types of resource potentials, the numbers behind which are estimated from data in Bertani (2010). In Appendix A we show the relationship between depth and temperature of geological

Table 2
Ground source heat pump capital costs.

Technology	Application	CAPEX [M\$/PJ/yr]	
		2010	2050
Heat pump	Commercial	37	32
Heat pump	Residential	95	81

Table 3
Geothermal direct use capital costs.

Technology	Heating	Application	CAPEX [M\$/PJ/yr]	
			2010	2050
Direct use conventional	Space	Residential	90	76
Direct use EGS	Space	Residential	135	114
Direct use conventional	Space	Commercial	87	74
Direct use EGS	Space	Commercial	131	111
Direct use conventional	Water	Residential	164	139
Direct use EGS	Water	Residential	246	209
Direct use conventional	Water	Commercial	161	137
Direct use EGS	Water	Commercial	242	206

formations, and project this topology in a 3×3 matrix that contains all our geothermal technology types as well as their resource potentials and cost levels.

2.3. Scenarios

TIAM-ECN is operated under input assumptions on policy measures, technology features, resource data and demand projections, while delivering outcomes in the form of policy recommendations, technology portfolios, energy (trade) flows and investment & price levels. TIAM-ECN allows for performing cost-based analysis under multiple scenarios – for the purpose of the present study we ran four of them, summarised in Table 4. The first one is a reference (i.e. ‘baseline’ or ‘business-as-usual’) scenario, called REF, in which current developments are extrapolated and fossil fuels continue to contribute the largest share of total energy supply. This scenario is a representation of what the global energy system may look like without the introduction of far-reaching climate policy. The second one is a stringent climate change control scenario, entitled REF_2DC, which implies a high likelihood (of around 70%) that the global average atmospheric temperature increase does not exceed 2°C. For this scenario we assume that the additional (anthropogenic) atmospheric radiative forcing does not exceed 2.6 W/m² (RCP2.6; see IPCC, 2014). The third one, called GEO, is a scenario that resembles REF in all respects, except for the assumption that, as a result of technological progress, steeper cost reductions are achieved for EGS than the values listed in Tables 1, 2 and 3. In this scenario we suppose that the costs of EGS reduce with a learning rate of 13% between 2010 and 2050, and thereby follow the learning-by-doing process that has been empirically observed for fracking technology as employed for enhancing the production of natural gas from deep geological formations (Fukui et al., 2017). The fourth one, called GEO_2DC, is a scenario that resembles REF_2DC in all respects, except for the hypothesis that steeper cost reductions are achieved for EGS than in the more conservative baseline case (like in the GEO scenario according to a learning rate of 13%). This scenario therefore combines optimistic technological progress for geothermal energy from deep formations with ambitious global climate action that matches the target of the Paris Agreement (COP-21, 2015). Table 4 summarizes the main features of our four scenarios.

As with any model, the outcome of scenario runs with TIAM-ECN is determined by the values of its input parameters, which is why our results should not be interpreted as forecasts, but rather as projections

² All costs reported in this paper are expressed in US\$(2005).

Table 4
Summary of scenarios.

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

of how the energy system could possibly develop in the future. For each of the hundreds of technologies simulated in TIAM-ECN across all main energy-producing and energy-consuming sectors of the economy, assumptions are made on e.g. their current costs, future cost changes, maximum penetration rates and conversion efficiencies. Energy demand projections are made on the basis of expectations regarding socio-economic factors such as population growth, GDP increase, and the realization of savings and the implementation of efficiencies. Other assumptions relate to, for instance, fossil fuel reserves in different parts of the world, renewable energy potentials, energy trade capabilities between regions, autonomous energy efficiency and decarbonization processes, as well as energy-climate policies implemented prior to the reference year at which TIAM-ECN is calibrated (2010). For details on these assumptions, see notably [Loulou \(2008\)](#); [Loulou and Labriet \(2008\)](#); [Kober et al. \(2014\)](#), and [van der Zwaan et al. \(2018\)](#). Although TIAM-ECN runs over a time span of more than 100 years, due to the rapid changes in the world energy system – for geothermal energy technology in particular – we focus in this study only until the horizon of 2050.

3. Results

[Fig. 1](#) shows the pathways for global geothermal electricity generation under our four scenarios obtained with TIAM-ECN (see Appendix A for the corresponding capacities). As can be seen, our baseline scenario is aligned with estimates for the growth of geothermal power production between 2020 and 2050 by publications from the [IEA \(2011\)](#) and [ESMAP \(2012\)](#), but our numbers remain lower than the ones quoted in these reports, which reflects that during recent years the use of geothermal energy has increased less rapidly than foreseen a decade ago. We find that under 2°C climate policy the geothermal electricity generation level may be over 200 TWh/yr higher in 2050 than the 800 TWh/yr foreseen in our reference projection. Similarly, under substantial technological progress the geothermal electricity generation level may be almost 200 TWh/yr higher in 2050 than the 800 TWh/yr foreseen in our reference projection. Under the combined effects of stringent climate policy and technological progress the

electricity generation level may become as high as 1300 TWh/yr in 2050. If no technological advancement materializes, EGS based technology may yield about 40% of the total amount of electricity generated in 2050. If optimistic technological change materializes, EGS may deliver over half of the total amount of geothermal power produced in 2050.

In [Fig. 2](#) we show our projections for global geothermal heat production under the four scenarios generated with TIAM-ECN (see Appendix A for the corresponding capacities). Our REF scenario is in principle in agreement with relative geothermal heat use growth pathways between 2020 and 2050 published in key studies by the [IEA \(2011\)](#) and [ESMAP \(2012\)](#), but our absolute numbers are lower than the ones reported in these seminal publications to reflect that during the second decade of this century the diffusion of geothermal energy usage has increased less rapidly than initially foreseen. We find that under substantial technological progress the geothermal heat production in 2050 may be around 500 TWh/yr higher than the approximately 3300 TWh/yr foreseen in our reference projection. In our reference scenario both conventional heat pumps and direct heat usage increase, with the former accounting for around two thirds of all heat generated in 2050, and the latter representing the remaining one third. We see that if stringent climate action materializes in the reference scenario, the total geothermal heat usage becomes substantially higher in 2040, while EGS based direct heat production remains negligible until 2050. If the REF scenario is complemented with optimistic technological change, overall heat usage increases, and EGS starts playing a substantial role from 2040 onwards, while it represents around 15% of the global geothermal heat generated in 2050. As can be seen, the two GEO scenarios resemble each other, except for a higher overall heat use in 2040 in the GEO_2DC scenario.

[Fig. 3](#) depicts the evolution of the global electricity supply mix until 2050 according to TIAM-ECN projections. About half of total electricity generation remains dominated by fossil fuels (coal and natural gas) if no stringent climate action is implemented, in agreement with most of the literature on the subject ([IEA-WEO, 2018](#); [IEA-ETP, 2018](#)). If climate policies in line with the ambitions of the Paris Agreement are adhered to, however, the breakdown of our projections drastically changes in favor of renewables such as solar and wind power. Options like CCS, hydropower and biomass-based technologies are also strongly stimulated by concerted climate action. We project that by 2050 geothermal power plants, partly in competition with (and partly supplementary to) other low-carbon energy technologies, could contribute by approximately 3% to global electricity generation if the promises of the Paris Agreement are fulfilled, and about 2% without orchestrated global climate policy.

[Fig. 4](#) plots our findings for global annual investments in geothermal

Fig. 1. Projections with TIAM-ECN for global geothermal electricity generation. Statistical data for 2010 are taken from [IEA \(2011\)](#), for 2020 they are derived from [IEA \(2019\)](#).

Fig. 2. Projections with TIAM-ECN for global geothermal heat production. Statistics for 2010 and 2020 are taken, respectively derived, from Lund and Boyd (2015) and Lund et al. (2015).

energy, split among four main options: conventional (power and heat, respectively) and EGS-based technology (power and heat, respectively). For heat usage we have only included numbers for the residential and commercial sector; once we have improved our modeling of geothermal energy use in industry and agriculture we may determine overall aggregate investment levels. Fig. 4 shows that if all nations stay on track of the Paris Agreement target by which the global average temperature increase is limited to 2°C, and if the costs of geothermal energy production from deep formations through EGS reduce optimistically with a learning rate of 13%, we project a market size for geothermal energy investments potentially worth about 500 billion US\$/yr by the middle of the century. We foresee that geothermal investment opportunities will grow exponentially, also in our baseline (REF) scenario, but the market may become significantly larger in scenarios under which geothermal energy technology develops and improves more favorably.

The investment numbers reported in Fig. 4 are undiscounted annual capital costs (CAPEX). The WACC for all geothermal technologies, except heat pumps, is assumed to be 12%. This WACC is higher than for other renewable electricity generation technologies (for which we adopt a WACC of 10%) to reflect the risks associated with exploration (i.e. the hit-and-miss ratio for well drilling). As can be seen, Fig. 4 includes the costs of both supply and demand side technologies, which is why these figures cannot directly be compared to those reported by e.g. McCollum et al. (2013), who report supply side numbers only. Fig. 4 shows that supply side (power) investments are an order of magnitude lower than overall (supply plus demand side, power and heat) investments. Supply side geothermal energy investments amount to around 50 billion US\$/yr in 2050, which corresponds to about 2–3% of the overall supply side energy investment requirements of around 2000 billion US\$/yr reported in cross-model comparison studies on stringent

Fig. 3. Projections with TIAM-ECN for the total global electricity supply mix.

Fig. 4. Calculations with TIAM-ECN for global annual investments in geothermal energy.

climate change control like McCollum et al. (2013).

4. Conclusions

With one of the leading integrated assessment models, TIAM-ECN, we have computed how much the use of geothermal energy 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: the generation of electricity and the production of heat. For the former we foresee a size of about 800–1300 TWh/yr by the middle of the century, depending on assumptions regarding climate ambition and technology progress for EGS. For the latter we project, under the same assumptions, a magnitude of around 3300–3800 TWh/yr in 2050. We estimate that by that year geothermal energy plants, partly in competition with renewables like PV and wind power as well as with coal and natural gas based power production, could contribute approximately 2–3% to global power generation. If all countries stay committed to the ambition of the Paris Agreement and correspondingly manage to keep the global atmospheric temperature increase below a maximum of 2°C, we foresee a total (supply plus demand side) geothermal energy investment market size possibly worth about 500 billion US\$/yr in 2050.

One of our underlying assumptions behind this investment level of 500 billion US\$/yr is that the costs of geothermal energy production from deep formations reduce with a learning rate of 13%. There is empirical evidence for this learning rate value, since it has been observed for fracking technology applied to natural gas fields, which is a similar technology to that used for enhancing geothermal systems. We project that this investment scale could be more than 100 billion US\$/yr lower in 2050 if this technological progress through learning-by-doing does not materialize. Yet even under such a setback, we project that the market size could still amount to over 350 billion US\$/yr by 2050. This finding yields confidence for geothermal energy project developers and, more generally, the private sector of geological exploration, since the geothermal energy sector is projected to become big business under different scenarios and varying assumptions.

In this study we have taken the work by Limberger et al. (2014) a step further. In their publication they determine the economic potential by calculating the levelized cost of electricity (LCOE) for geothermal resources in Europe on the basis of the technical potential that they

deduce from detailed information of underground temperature gradients and formation porosities. They compare the resulting LCOE values with reference levels at several points in time until 2050 at which they assume competitiveness is reached with LCOE figures for incumbent alternatives. Limberger et al. (2014) do not account for the fact that LCOE levels of renewable and fossil-based alternatives are themselves dependent on developments in multiple sectors of the economy and thus intrinsically subject to change. We argue that, in order to more closely reflect reality, one should not adopt static benchmarks for LCOE values *a priori*. We correct for this shortcoming in Limberger et al. (2014) by using the TIAM-ECN model, so as to get a better sense of what the economic potential for geothermal energy could be. Furthermore, we run this IAM for the world as a whole, rather than only at the European level, in order to estimate what the role of geothermal energy could be in the international energy transition and global climate change mitigation. Limberger et al. (2014) find an economic potential for geothermal energy in 2050 exceeding 500 GW for Europe alone. We, on the other hand, obtain a maximum aggregated capacity of less than 200 GW for geothermal power generation in 2050 for the entire world (see Appendix A). Given this contrast, we conclude that it is important to carefully select the methodology with which one attempts to determine economic resource potentials for geothermal energy, and that it may matter significantly whether one uses a static approach (as adopted by Limberger et al., 2014) 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 manner in which we model global geothermal energy pathways with TIAM-ECN is still subject to a number of shortcomings. Our future research plans and model development therefore include addressing these deficiencies, with the purpose of improving our projections for global geothermal energy diffusion. A first topic we would like to investigate in more depth is the high cost – high risk nature of geothermal energy projects. This market imperfection (limited hit-and-miss ratio) has held back the growth of the geothermal energy sector, even though geothermal energy can deliver both heat and power at competitive prices. Without some sort of mechanism to absorb the upstream risk during the exploration phase, the geothermal sector may find it hard to compete for investors' attention against the reality of less risky renewables. We do not know whether we can properly assess the risk aspects of geothermal energy development through a model like TIAM-ECN beyond the means that it currently possesses to reflect this risk (see

the CAPEX and WACC description in the Methodology section; another option to explore would be exploiting the model's stochastic version). Perhaps one should use another more dedicated tool, but it is evident that this subject deserves further attention.

A second task we would like to undertake is to better represent geothermal energy resource potentials. We currently do this rather stylistically using approximate aggregations of technical potentials for the 36 world regions in TIAM-ECN. By refining the geographical representation of resource potentials we could better quantify the typically large regional differences in geothermal energy deployment opportunities. We intend to use the geographically much more detailed and high-resolution information available on technical resource potentials such as from the ThermoGIS database (ThermoGIS, 2019)³. Other relevant topics in this area are economic resource potential limitations as a result of the distance between geothermal energy production and the locations where geothermal power or heat is consumed (the transportation costs differ between these two alternatives), as well as the possibly limited longevity of the geothermal energy resource base at individual production sites. Another interesting resource-related research question that falls beyond the scope of the present study is whether competition could materialize between conventional geothermal and EGS-based technology.

We also would like to simulate with higher accuracy geothermal energy usage in industry and the agricultural sector, since to date we only do this rudimentarily for just a few applications and thus far have mostly focused on its use in the power, residential and commercial sectors. Ideally, we would ultimately complement these improvements by also representing subsequent 'heat cascades'. In such repetitive cascading processes high-temperature heat usage in, for instance, industrial applications is followed by the use of ensuing low-temperature waste heat streams in e.g. the residential or commercial sector. To reflect the economics of heat usage we currently reflect differences between seasons as well as between day and night (by the use of so-called 'time-slices'; see e.g. van Stralen et al., 2018), but in future research we may want to refine the granularity of these features in order to enhance our projections for (geothermal) heat demand in all relevant sectors.

For the present study we have not considered an important feature

of conventional geothermal energy technologies, which is the possibility that CO₂ is emitted by using heat directly from the underground (see, for example, Bertani and Thain, 2002; Bloomfield et al., 2003; Rybach and Mongillo, 2006). The operation of geothermal technologies in some regions (e.g. New Zealand) clearly causes CO₂ emissions. This may have negative effects for the deployment of geothermal technologies using underground steam directly, and could have more generally implications for the role of geothermal energy under stringent climate policy. We think that future studies should inspect this issue, and that analysts may need to account for it in their models. Since renewable energy technologies at large sometimes yield low but non-zero greenhouse gas emissions, we expect this subject more generally to soon become more important for the goal of achieving net zero CO₂ emissions by 2050.

Overall, we recommend that the entire IAM community (see e.g. IAMC, 2019) undertakes improvements with regards to the representation of geothermal energy production and consumption options in its arsenal of models, since the role of geothermal technologies in the transformation of energy infrastructures is likely to grow substantially, as previously projected in the literature and now confirmed by our results (even while we project substantially lower growth rates than e.g. IEA, 2011 and Limberger et al., 2014). Such research ought to be accompanied by studies of social acceptance, because the optimism expressed in this article could be tempered by public concerns over possible environmental impacts of geothermal energy use (for fracking technology in particular) or over potential seismic consequences of drilling, extraction and injection activities (a delicate subject in e.g. the Netherlands).

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Appendix A

In Fig. A1 we show the topology structure for all geothermal energy options that are currently represented in TIAM-ECN's 36 regions. In its present version, we distinguish between three depth levels (vertical axis): shallow (0–200 m), deep (200–2000 m) and ultra-deep (> 2000 m). We characterize three temperature levels (horizontal axis): low (0–100°C), medium (100–200°C) and high (> 200°C). Greater depths are characterized by higher temperatures, as stylistically indicated for two types of geological formations: sedimentary basins and volcanic systems, respectively. Power generation requires high temperatures, while low and medium temperatures suffice for direct heat usage. We distinguish between three resource potential levels (low, medium and high) that increase with depth and decrease with temperature. A low (high) resource potential implies a low (high) geographical likelihood that the geothermal technology can be made available or, alternatively, that the encountered conditions are such that it can be deployed at a small (large) number of locations. The resource potentials we use in TIAM-ECN are based on data from Bertani (2010) that we matched with the geographical resolution of our model. We assume four cost levels (existing/lowest, low, medium and high) depicted in Fig. A1 with the symbols \$, \$\$, \$\$\$ and \$\$\$\$ respectively. A direct relation exists between the geothermal technologies in Fig. A1 and their costs listed in Tables 1, 2 and 3.

Fig. A2 shows the pathways for global geothermal electricity capacity under our four scenarios obtained with TIAM-ECN. The REF scenario is in principle aligned with estimates for the growth of geothermal power capacity between 2020 and 2050 by publications such as from the IEA (2011) and ESMAP (2012), but we have downscaled our scenarios with respect to theirs, since these publications prove to have given overly optimistic projections for 2020. We find that under 2°C climate policy and substantial technological progress the overall capacity may be around 60 GW higher in 2050 than the 110 GW foreseen for that year in our reference projection. We see that if no technological innovation materializes, EGS based technology may represent about 40% of the total geothermal capacity in 2050. If optimistic technological change occurs, it may yield slightly over half of the global geothermal capacity in 2050.

Fig. A3 shows the pathways for global geothermal heat capacity under our four scenarios obtained with TIAM-ECN. The REF scenario is in principle in line with estimates for the growth of geothermal heat capacity between 2020 and 2050 by studies from the IEA (2011) and ESMAP (2012), but our 2050 numbers are lower than those foreseen by these reports since we account for the fact that their projections for 2020 have fallen short of the actual realization. We find that under substantial technological progress the capacity may be close to 200 GW higher in 2050 than the

³ The ThermoGIS database is publicly available, with full geographical detail for the Netherlands, and in the near term also, according to current plans, for Europe and possibly the rest of the world.

Fig. A1. Topology of geothermal options in TIAM-ECN, distinguished by 3 potential levels (low, medium, high) and 4 cost levels (existing, low, medium, high: \$, \$\$, \$\$\$, \$\$\$).

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

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

almost 600 GW foreseen in our reference projection. In our reference scenario conventional heat pumps and direct heat usage co-evolve in approximate equilibrium. We see that if innovation-driven cost reductions materialize, EGS based direct heat use may represent about 25% of the total geothermal heat capacity in 2050. Under optimistic technological change, EGS based direct heat use starts contributing at the 10% level to the global geothermal heat capacity from 2040 onwards.

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