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Geothermal Electricity: Potential for CO² Mitigation

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1 Introduction

The provision of energy addresses societal and political issues for the present and future generations. A goal, which is defined in the Kyoto and post-Kyoto targets, is to increase the share of renewable energies in the future energy concepts, in order to mitigate greenhouse gas emissions and reduce the consumption of finite energy resources. The development of geothermal energy for electricity production and particularly the use of Enhanced Geothermal Systems (EGS) are promising options in this context. EGS are supposed to make a large contribution to a sustainable energy mix, in the future. This means that, besides improving technical aspects, the use of geothermal energy must be realizable with a climate friendly lifecycle and competitive energy production costs.

In the present study the potential of geothermal electricity regarding CO₂ mitigation will be discussed, considering CO₂-emissions of different energy sources and particularly of the different geothermal power plants on-line today. Technical potential deployment is estimated based on different literature sources and the resource assessment study developed within the framework of the GEOELEC Project. CO₂-mitigation calculations of different studies will be discussed considering the technical potential.

2 CO₂ emission by electricity generation from different energy sources

Worldwide

In 2010, CO₂ emissions from fuel combustion in general (considering energy and heat generation, transport, industry and others) were generated by coal (43%), oil (36%) and gas (20%). Growth in emissions from these fuels in 2010 was not uniform, reflecting varying trends that are expected to continue (Figure 1).

Between 2009 and 2010, CO₂ emissions from the combustion of coal increased by 4.9% and represented 13.1 Gt CO₂. Currently, coal fills much of the growing energy demand of those developing countries (such as China and India) where energy-intensive industrial production is growing rapidly and large coal reserves exist with limited reserves of other energy sources.

CO₂ emissions from oil represented 10.9 Gt CO₂ in 2010, an increase of 2.7%. Hence, the decreasing relative contribution of oil to the total primary energy supply is a result of the growth of coal and gas (IEA, 2012).

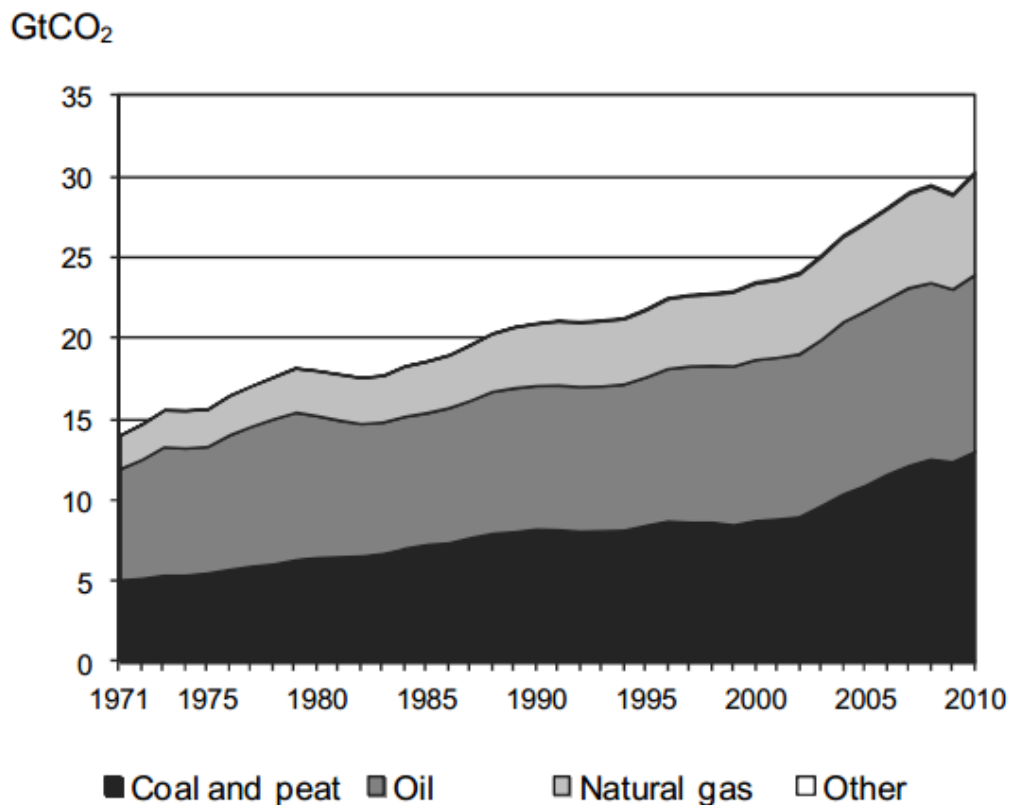


Figure 1: CO₂ emissions by fuel combustion (IEA, 2012).

Two sectors produced nearly two-thirds of the global CO₂ emissions in 2010: electricity and heat generation accounted for 41% while transport produced 22% and industry 20% (Figure 2).

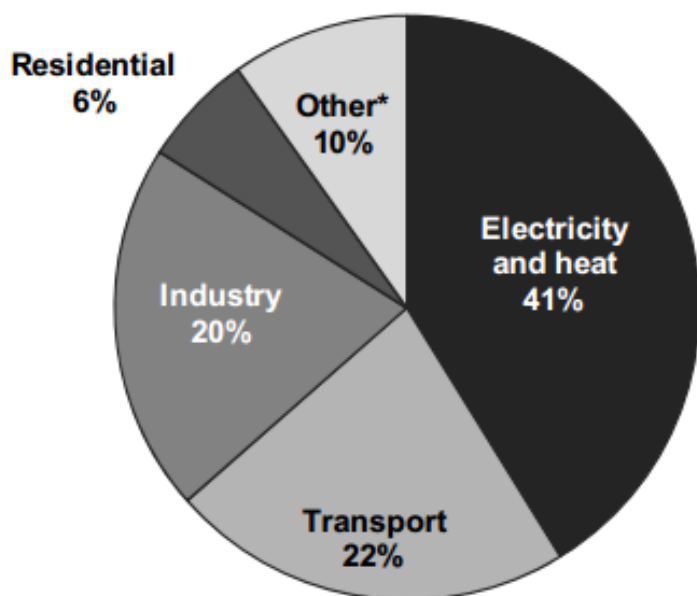


Figure 2: World CO₂ emissions by sector in 2010 (IEA, 2012). *Other includes commercial/public services, agriculture/forestry, fishing, energy industries other than electricity and heat generation, and other emissions not specified elsewhere.

Considering only the CO₂ emissions from the generation of electricity and heat an increase between 2009 and 2010 of 5.6% occurred (Figure 3). CO₂ emissions from oil increased the least, by 0.3%, while more substantial increases were seen for coal (4.7%) and gas (9.5%). Future development of the emissions intensity of this sector depends strongly on the fuels used to generate electricity and on the share of non-emitting sources, such as renewables and nuclear energy.

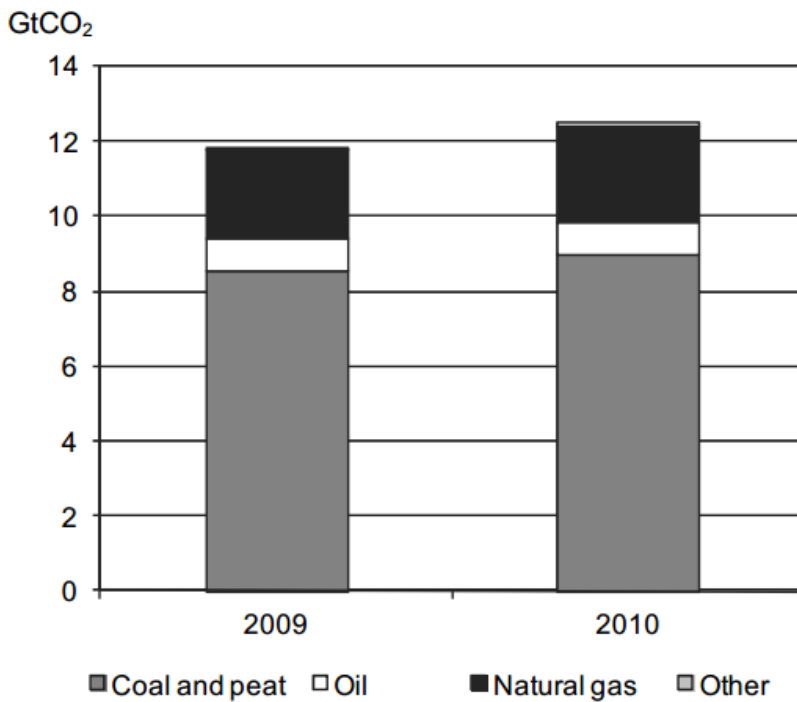


Figure 3: World CO₂ emissions of electricity and heat generation in 2010 (IEA, 2012).

Europe-wide

Regarding the relative CO₂ emissions of different sectors, the situation in Europe differs from the global situation (Figure 4) with a lower portion of electricity and heat production (33%) and higher portions of transport (27%) and residential (13%).

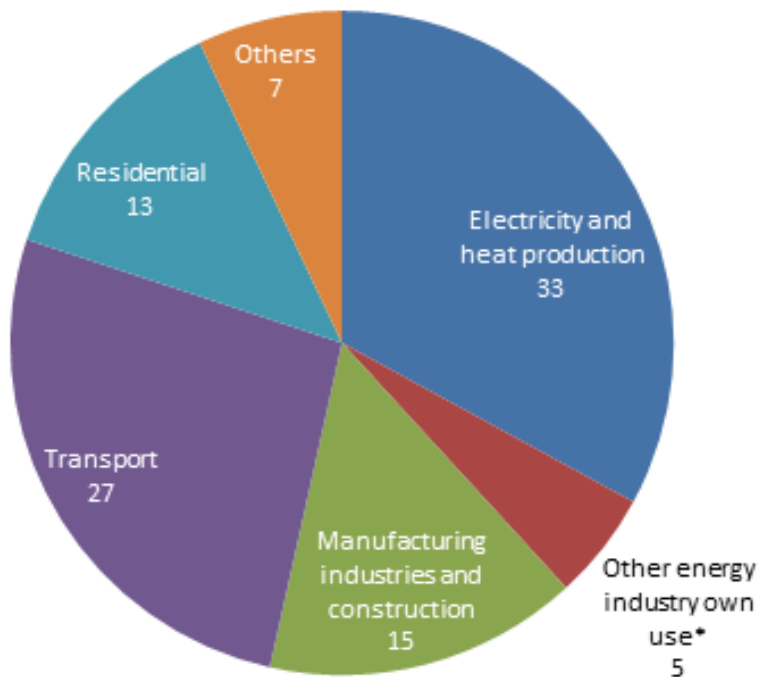


Figure 4: European CO₂ emissions by sector in 2010 (%).

Table 1 gives a detailed overview of the CO₂ emissions of the different sectors in Europe in 2010. Energy and heat production produce the largest part with 1006.6 Mt CO₂, followed by transport (811.4 Mt CO₂) and industry (467.9 Mt CO₂).

Table 1: European CO₂ emissions by sector in 2010 (Mt CO₂) (IEA, 2012).

Total CO ₂ emissions from fuel combustion	Electricity and heat production	Other energy industry *	Manufacturing industries and construction	Transport	Residential	Others
3056.6	1006.6	160.7	467.9	811.4	394.6	215.5

*Includes emissions from own use in petroleum refining, the manufacture of solid fuels, coal mining, oil and gas extraction and other energy-producing industries

The CO₂ emissions from electricity generation in Europe decreased between 1995 and 2010, particularly the emissions of oil and gas declined. Emissions resulting from gas combustion remained almost constant (Figure 5).

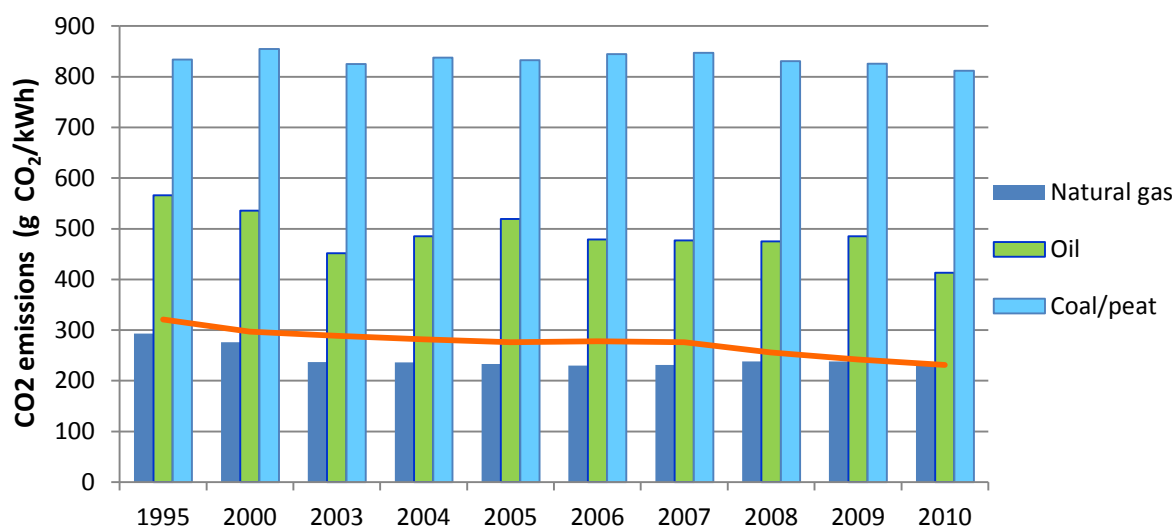


Figure 5: CO₂ emissions per kWh from electricity generation in Europe.

Table 2 gives the CO₂ emissions per kWh from electricity generation in Europe, as shown in Figure 5 and further the energy mix data from 1995 to 2010. The energy mix is calculated considering CO₂ emissions from fossil fuels consumed for electricity generation, in both electricity-only and combined heat and power plants, divided by output of electricity generated from fossil fuels, nuclear, hydro (excl. pumped storage), geothermal, solar, wind, tide, wave, ocean and biofuels. Both main activity producers and autoproducers have been included in the calculation. The values decrease from 321 g CO₂/kWh (1995) to 231 g CO₂/kWh (2010), indicating the decreasing contribution of fossil fuels to the electricity and heat generation.

Table 2: CO₂ emissions per kWh from electricity generation in Europe (g CO₂/kWh) (IEA, 2012).

year	1995	2000	2003	2004	2005	2006	2007	2008	2009	2010
Energetic mix*	321	297	289	282	276	278	276	256	242	231
Natural gas	293	276	237	236	233	230	231	238	238	236
Oil	566	536	452	485	519	479	477	475	485	413
Coal/peat	834	855	825	838	833	845	847	831	826	812

Table 3 gives the CO₂ emissions in megaton (Mt) occurring in the electricity and heat generation sector between 1995 and 2010 considering the different fuel types, which again shows the decrease in CO₂ emissions of oil and further of coal/peat combustion partly replaced by natural gas.

Table 3: CO₂ emissions - sectoral approach in Europe (Mt CO₂) (IEA, 2012).

year	1995	2000	2005	2008	2009	2010
Natural gas	631.3	783.8	894.7	907.4	856.8	910.8
Coal/peat	925.1	843.1	849.8	795.9	685.2	709.4

Lifecycle assessment data

The data presented for Europe and worldwide showed CO₂ emissions of the production process. In order to characterize CO₂ emissions by power plants one has to clearly distinguish between data which only consider CO₂ emissions occurring during the power production process and data considering the whole lifecycle of a power plant. Lifecycle assessment (LCA) studies account not only for the power production process but also for CO₂ emissions related to pre-chains of installed components, used material and necessary services. The National Renewable Energy Laboratory (NREL) carried out a comprehensive review of published LCAs of electricity generation technologies based on a huge amount of references which were screened concerning quality and relevance (Moomaw et al., 2011). The results of greenhouse gases (g CO₂eq/kWh) emitted by electricity generation technologies using natural gas, oil and coal resources are shown in Figure 6. Natural gas shows the lowest values with a minimum of 290 g CO₂eq/kWh, a maximum of 930 g CO₂eq/kWh and a median of 469 g CO₂eq/kWh. The minimum emissions from oil are 510 g CO₂eq/kWh, with a maximum of 1170 g CO₂eq/kWh and a median of 840 g CO₂eq/kWh. Coal shows the highest values with a minimum of 675 g CO₂eq/kWh, a maximum of 1689 g CO₂eq/kWh and a median of 1001 675 g CO₂eq/kWh.

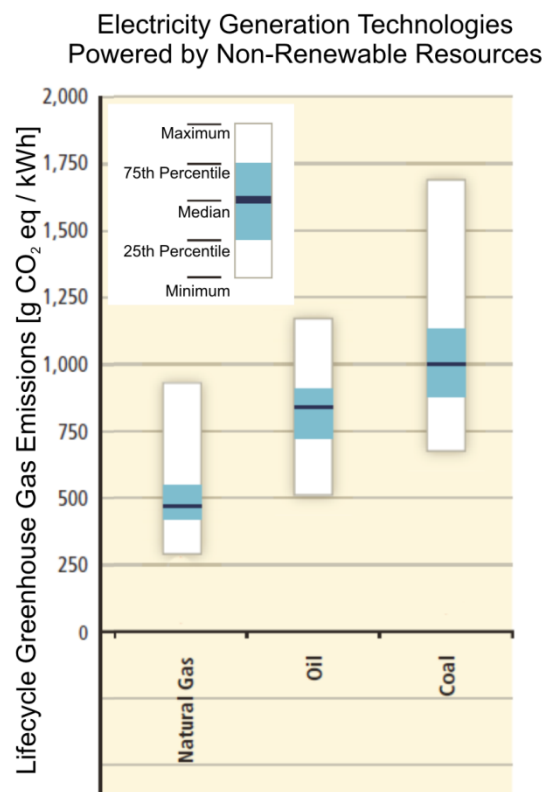


Figure 6: Estimates of lifecycle GHG emissions (g CO₂eq/kWh) for non-renewable resources (modified after Sathaye et al., 2011). References and methods for the review underlying this figure are reported in Moomaw et al. (2011).

3 CO₂ emission by electricity generation from geothermal power plants

The natural geothermal systems are high-enthalpy or high-temperature geothermal systems and the largest part of geothermal energy so far used is generated from these reservoirs (e.g. Italy, Iceland). However, a large geothermal potential lays in the unexploited low-temperature (typically between 100 and 200°C) reservoirs, as they are much more frequent. These reservoirs can be called man-made reservoirs, as they often occur in great depth and show insufficient natural permeability and fluid saturation and hence technical measures are needed to enhance such geothermal reservoirs (EGS). Thus one can distinguish between natural geothermal systems and EGS.

Emission rates associated with geothermal power plants are much lower than emissions from coal or gas-fired power plants. However, to quantify CO₂ mitigation by deployment of geothermal energy utilization it is necessary to quantify the CO₂ emissions from geothermal power plants as well. Again one has to distinguish between CO₂ emissions occurring during the power production process and CO₂ emissions occurring during the whole lifecycle process, furthermore geothermal/volcanic systems emit gases naturally. Zero emissions can only occur when the power production process is considered solely but never when the whole lifecycle is included.

In the following the recent results concerning CO₂ emissions related to geothermal electricity production are examined, considering the aforementioned aspects and differentiating between (1) geothermal power plants using an open system (2) new geothermal power plants using a closed system and (3) EGS geothermal power plants using a closed system.

Natural emissions from geothermal reservoirs

In high-enthalpy or high-temperature geothermal reservoirs gases emit naturally. The gases naturally vent to the atmosphere through diffusive gas discharges from areas of natural leakage, including hot springs, fumaroles, geysers, hot pools, and mud pots. CO₂ is the most widely emitted gas, but geothermal fluids can, depending on the site, contain a variety of other minor gases, such as hydrogen sulphide (H₂S), hydrogen (H₂), methane (CH₄), ammonia (NH₃) and nitrogen (N₂). Mercury, arsenic, radon and boron may be present (Goldstein et al., 2011). Thus to what extent gases emit to the atmosphere depends on the geological, hydrological and thermodynamic conditions of the geothermal field. The question was raised if in such systems emissions of geothermal power production are negligible in comparison to natural emissions. Bertani and Thain (2002) analyzed this question considering data from the Larderello geothermal field (Italy) and they concluded that all gas discharge resulting from power production is balanced by a reduction in natural emissions. However, a study conducted in Iceland by Ármannsson et al. (2005) showed different results. The analysis of CO₂ emission from the three major geothermal power plants in Iceland was $1.6 \cdot 10^8$ g in 2002, which is essentially equal to the natural CO₂ discharge from Grímsvötn, the most active volcano in Iceland.

Natural gas emissions are restricted to geothermal/volcanic systems; this problem is not a matter of consequences for the deployment of EGS.

Geothermal power plants in operation using an open system

In dry and flash steam plants, noncondensable gases are separated from the steam turbine exhaust in the plant condenser and are either discharged to the atmosphere or removed by an abatement system. Abatement systems so far prevent the release of hydrogen sulfide and elementary mercury; however, also CO₂ discharge can be prohibited by recovering liquid carbon dioxide (Nolasco, 2010).

Several studies deal with the quantification of CO₂ emissions during the power production process through geothermal power plants using an open system. Ármannsson et al. (2005) analyzed CO₂ emissions from Icelandic geothermal power plants. They evaluated data of three dry steam geothermal power plants and received CO₂ emissions between 26–181 g/kWh.

In the study of Holm et al. (2012) CO₂ emissions from different geothermal facilities in California were reported. The data were taken from publicly available geothermal facility reports (see Figure 7). They report an emission for dry and flash steam plants of about 5% of the CO₂, 1% of the sulfur dioxide (SO₂), and less than 1% of the nitrous oxide (N₂O) emitted by a coal-fired plant of equal size. The weighted average CO₂ emission of flash steam plants is 180 g/kWh and of dry steam plants 27 g/kWh.

Bertani and Thain (2002) obtained CO₂ emission data from 85 geothermal power plants operating at this time in 11 countries around the world. The collected data show a wide spread in the overall CO₂ emission rate from the plants. The authors report a range of 4 g/kWh to 740 g/kWh with the weighted average being 122 g/kWh. From the collected data, the average CO₂ content in the non-condensable gas is 90.5%.

Geothermal power plants in operation using a close system

Binary power plants retain noncondensable gases in a closed loop system; the thermal water is reinjected after utilizing its heat at the heat exchanger. The result is near-zero emissions during the power production process as the noncondensable gases are never released to the atmosphere (Holm et al., 2012). However, if gas separation occurs within the circulation loop, some minor gas extraction and emission is likely (Goldstein et al., 2011).

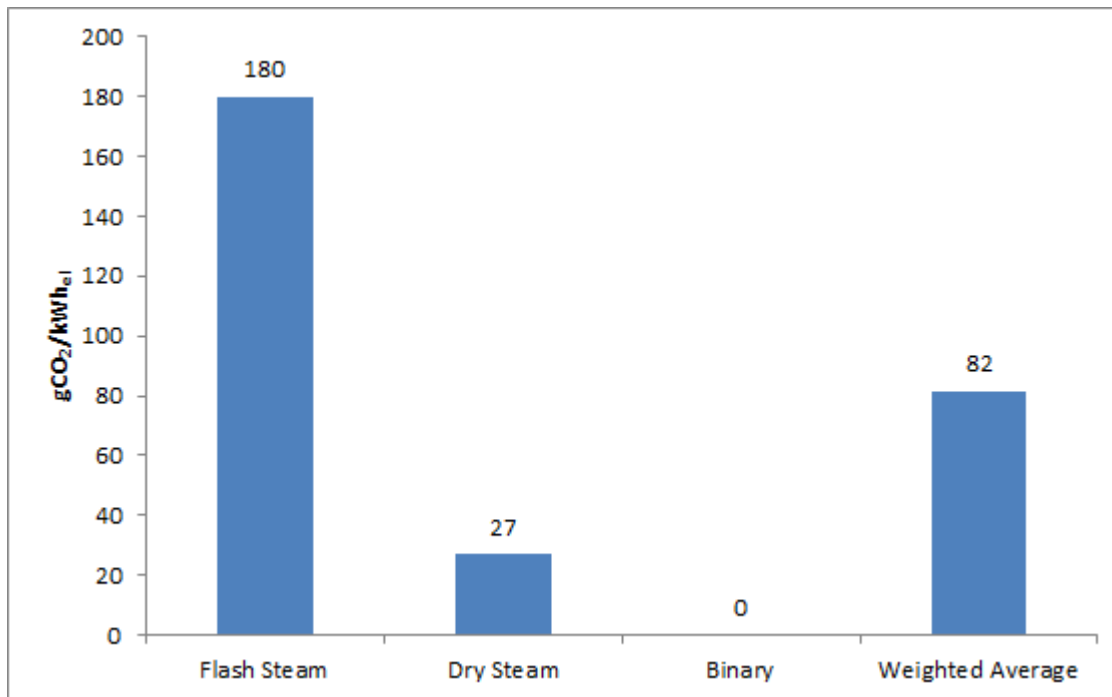


Figure 7: Average of geothermal CO₂ emissions occurring during the power production process of different technologies from California (Holm et al., 2012).

EGS geothermal power plants in operation

For the generation of power from such systems closed-loop cycles are used and gaseous pollutants are not emitted during plant operation similar to binary power plants. Hence, EGS binary power plants can be assumed to be in most cases free of CO₂ emissions considering only the production process and natural emission of gases do generally not occur in these reservoirs.

Lifecycle assessment data

Frick et al. (2010) did a LCA of EGS geothermal binary power plants considering CO₂ emissions not emitted during plant operation but during construction, the value is relatively low (~60 g CO₂eq /kWh). They compared geothermal binary power plants with reference electricity and a reference heat mix which showed that they have significantly lower emissions of CO₂-equivalent pollutants. Further NREL analyzed in the comprehensive review of published LCAs of electricity generation technologies also geothermal energy (Figure 8, Sathaye et al., 2011; Moomaw et al., 2011). They give a minimum value of 6 g CO₂eq/kWh, a maximum of 79 g CO₂eq/kWh and a median of 45 g CO₂eq/kWh. However, the data rely on six references (including the study of Frick et al., 2011), which not only considered EGS binary power plants but geothermal power plants in general. This can explain the slightly lower mean value of 45 g CO₂eq/kWh compared to the value given by Frick et al. (2010) 60 g CO₂eq /kWh.

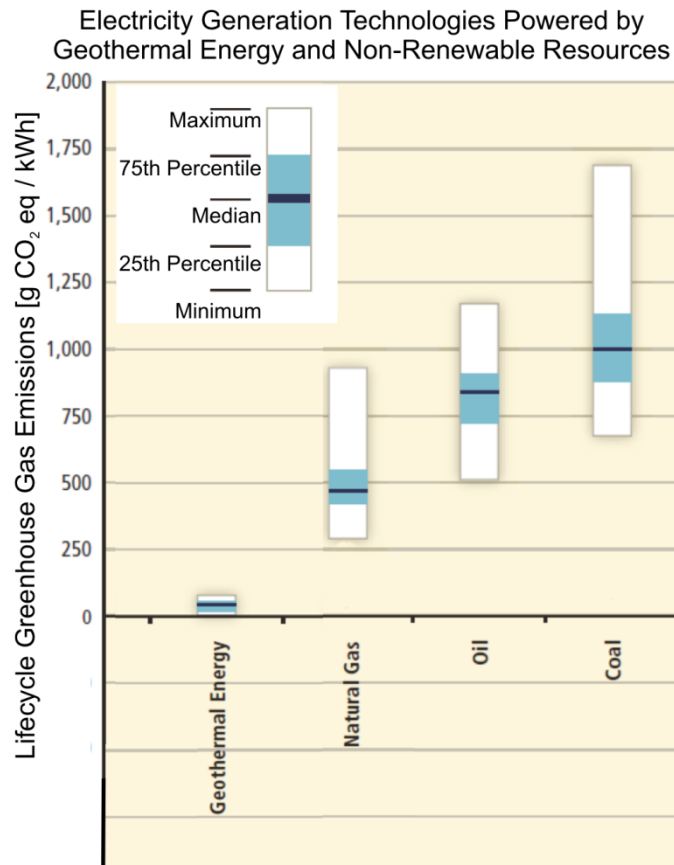


Figure 8: Estimates of lifecycle GHG emissions (g CO₂eq/kWh) for geothermal energy and non-renewable resources (modified after Sathaye et al., 2011). References and methods for the review underlying this figure are reported in Moomaw et al. (2011).

4 Potential deployment

4.1 Future market

Overall, the geothermal–electricity market increases, as indicated by the trends in both the number of new countries developing geothermal energy and the total of new megawatts of power capacity under development. It is, however, difficult to predict future rates of deployment, because of the numerous variables involved. Within the framework of the Geoelec Project the geothermal potential in Europe was evaluated mainly based on the integration of existing data provided by the 28 European member (EU-28) countries and a newly defined methodology building on Canadian, Australian, and American methodology and based on concepts developed in the oil and gas industry, which were adopted for geothermal resource assessment. Temperature–depth maps and rock types were used as input parameters to determine a theoretical potential. Further an economical potential for 2030 and 2050 for EGS is estimated by assuming a Levelised Cost of Energy (LCoE) value of less than 150 €/MWe for the 2030 scenario and less than 100 €/MWe for the 2050 scenario. The results of this resource assessment study state that a yearly contribution of geothermal electricity in 2030 of

34 TWh for EU-28 and 174 TWh for all of Europe is possible. For 2050 the study gives a potential of 2570 TWh for EU-28 and 4000 TWh for Europe.

In the IPCC report (2011) a very detailed description of the geothermal potential worldwide is given by Goldstein et al. (2011), they distinguish between the general resource potential and the global technical potential. They estimate the technical potential of geothermal resources for electricity generation worldwide to range between ~1990 GW and ~970 GW and the EGS technical potentials to be ~4120 GW (down to 3 km depth) and ~38900 GW (down to 10 km depth) referring to the study of Stefansson (2005).

Fridleifsson (2008) assumed in his study an increase from the current value of 10 GWe installed capacity, up to about 140 GWe worldwide by 2050, which is less than the economic potential and the technical potential given in the GEOELEC study and the study of Goldstein et al. (2011). With the present engineering solutions, the gradual introduction of new technology improvements is expected to boost the growth rate, with exponential increments after 10–20 years. Some of the new technologies (for example, binary plants) have already been proven and are now rapidly deploying, whereas others are entering the field demonstration phases to prove commercial viability (EGS), or early investigation stages to test practicality (supercritical temperature and offshore resources).

Low temperature power generation with binary plants has opened up the possibilities of producing electricity in countries that do not have high temperature resources. EGS technologies (deep drilling, stimulation, and pumping) are being developed to access resources in this setting. Supercritical and offshore resources are also under investigation. If these technologies can be proven economical at commercial scales, the geothermal market potential could be limited only by the size of the grid or load in many countries of the world. It is anticipated that, by 2050, approximately half of the deployed capacity could come from these new technologies. Direct use of geothermal energy for heating is currently commercially competitive, using accessible hydrothermal resources. A moderate increase is expected in the future development of such hydrothermal resources for direct use, mainly because of dependence on resource proximity, and therefore on local economic factors.

4.2 Controlling factors of geothermal deployment

Technological factors

Direct heating technologies, district heating, and EGS methods are available. These have different degrees of maturity. The direct use of thermal fluids from deep aquifers, and heat extraction using EGS, have costs and risks, which can be reduced by further technical advances associated with accessing and engineering fractures in the geothermal reservoirs. The latter requires a better knowledge and measurement of the subsurface stress fields. For EGS, further remaining challenges are drilling, well completion, brine management, mitigation of induced seismicity, reliability of system components, and mitigation of corrosion and scaling. Knowledge acquired while developing geothermal reservoirs will lead to better practices and standards and increased deployment confidence. Geothermal power generation technologies also have different degrees of maturity. Reducing subsurface exploration risks will contribute to more efficient and sustainable development.

The drilling of high temperature reservoirs requires advanced technologies to prevent reservoir damage by drilling mud; an example is the use of balanced drilling procedures. Improved utilization efficiency requires better auxiliary energy use and improved performance of surface installations. Better reservoir management, with improved simulation models, will optimize reinjection strategy, avoid excessive depletion, and plan future make-up well requirements, to achieve sustainable production.

The quality of the heat extracted, and its potential diversity of use, increases with heat source temperature. Improvements in energy utilization efficiency from cascaded use of geothermal heat are an important deployment strategy. Evaluating the performance of geothermal plants, including heat and power EGS installations, will consider heat quality of the fluid by differentiating between the energy and the exergy content (exergy = the part of the energy that can be converted to power).

Economic and political factors

Distributions of potential geothermal resources vary from being nearly site-independent (e.g., EGS) to site-specific (for hydrothermal sources). The distance between electricity markets or centers of heat demand and geothermal resources is a factor in the economics of power generation and direct use. When making development choices, there is sometimes a trade-off between the quality of hydrothermal resources and their remoteness from secure grid connections or demand centers. The renewable, reliable, and cost-competitive nature of geothermal energy has, in the past, attracted some energy-intensive industries (e.g., aluminum smelting, pulp and paper, timber drying) to collocate with geothermal resources to attain a comparative commercial advantage. In the context of mandates for increased use of renewable energy and for reductions in GHG (greenhouse gas) emissions, this collocation trend is expected to increase. At present, growth in direct-use demand is dominated by single building applications for shallow ground-source heat pump systems, where the cost of energy distribution is not an issue. The direct use of heat from hydrothermal systems and EGS projects can satisfy the demand of district heating systems and industrial heating more effectively, but only where the politics, economics, and infrastructure of heat distribution are favorable.

The deployment of all technologies relies on the availability of skilled installation and service companies. For deep geothermal drilling and reservoir management, such services tend to be concentrated in a few countries only. For district heating, there is also a correlation between local availability and awareness of service companies, and technology uptake. For enhanced global deployment, such services would be better distributed worldwide. Larger deployment is generally facilitated by establishing insurances to cover drilling, development, and production risks. Therefore, project risk management is another requirement for financing, installing, and operating large geothermal installations. Prior knowledge and expertise within the local banking and insurance industries generally assist in accelerating local deployment rates. Geothermal deployment will be supported, politically, by a CO₂-mitigation strategy, through establishing incentives for market penetration of geothermal energy supply technologies. These incentives can include, for example, subsidies, guarantees, and tax write-offs to cover the risks of initial deep drilling. Policies to attract energy-intensive industries (e.g., aluminum smelting) to known geothermal resource areas can also be useful. Feed-in tariffs with confirmed geothermal prices have been very successful in attracting commercial investment in some countries (e.g., Germany). However, feed-in tariffs for direct heating

are difficult to arrange. Therefore, direct subsidies for building heating and for district heating systems may be more successful. Subsidy support for refurbishment of existing buildings with geothermal energy will open a much greater market for future deployment. Policy support for research and development is required for all geothermal technologies, but especially for EGS. Public investment in geothermal research drilling programs should lead to a significant acceleration of EGS deployment.

Support is also needed for programs to educate and enhance public acceptance of geothermal energy use, and to conduct research toward the avoidance or mitigation of potential induced hazards and adverse effects.

5 CO₂-mitigation potential of geothermal power plants

To quantify the CO₂-mitigation potential of geothermal energy Huenges and Frick (2010) presented a scenario where geothermal power substituted coal and gas fired power plants. The scenario was developed in the framework of the IPCC report, which provided several scenarios for a reasonable development of the capacity of geothermal plants worldwide (Friedleifsson et al., 2008). It is assumed that a capacity of 10 GW in the year 2010 can be extended to a capacity of 140 GW in the year 2050 with a yearly contribution of about 1000 TWh (see Figure 9) worldwide. Half of the future capacity is expected to be contributed by EGS plants. The substitution of coal fired power plants by extended geothermal energy provision, which can be reached in the year 2050, mitigates every year more than 1 gigatons CO₂-emissions. This scenario is related to sites with normal geothermal gradients and can become much more favorable for EGS in preferred geothermal environments. It shows very well the high potential of geothermal power for CO₂ mitigation even with this relatively conservative estimate.

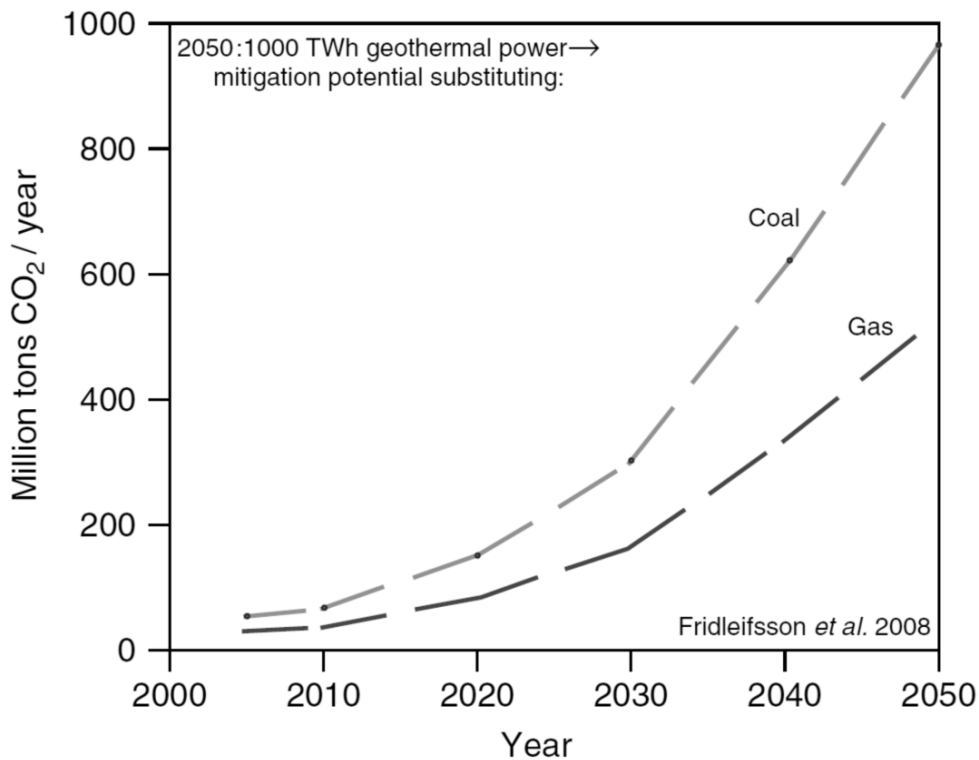


Figure 9: CO₂-mitigation calculation based on a forecast of the development of installed capacity of geothermal electricity up to about 140 GW providing about 1000 TWh from about 10 GW providing about 70 TWh in the year 2010.

Bertani and Thain (2002) calculated CO₂ mitigation based on the results of CO₂-emission rates of the data they obtained from dry and flash steam geothermal power plants worldwide. They report that replacing a combined cycle natural gas fired plant with a geothermal power plant having a CO₂-emission rate of 55 g/kWh would give a net saving of 260 g/kWh of generation. Similarly, if an oil plant is replaced the net saving would be 705 g/kWh, and for a coal-fired plant the saving would be 860 g/kWh.

6 Conclusion

Fossil fuels are still responsible for the vast majority of CO₂ emissions and the deployment of geothermal power production replacing coal or gas fired power plants could significantly contribute to a reduction of CO₂ emissions.

So far around 11% of the installed capacity of geothermal electricity in the world in 2009 was composed of binary plants (Bertani, 2010) which have near zero emissions during the production process. Hence, focusing within the geothermal technologies on these advanced technologies could further improve the sustainable energy supply.

The EGS technology has an enormous potential as shown by the GEOELEC resource assessment study where the geological potential was translated to an economical potential which revealed values of 21.2 TWh for EU-28 and 70.8 TWh for all of Europe in 2020. EGS geothermal power plants like binary geothermal power plants have basically zero CO₂ emissions during the production process and also from cradle-to-grave point of view low CO₂ emissions have been shown by the lifecycle analysis of Frick et al. (2010). However, the EGS technology needs further research particularly to improve technical advances associated with accessing and engineering fractures in the geothermal reservoirs. Knowledge and measurement of the subsurface stress fields is therefore indispensable and further remaining challenges are drilling, well completion, brine management, mitigation of induced seismicity, reliability of system components, and mitigation of corrosion and scaling. Public investment in geothermal research drilling programs is necessary to achieve acceleration in the EGS deployment and to take advantage of the base load potential of this energy and to establish it in the future renewable energy supply.

References

- Ármansson, H., Thráinn, F., Kristjánsson, B. R. (2005). CO₂ emissions from geothermal power plants and natural geothermal activity in Iceland, *Geothermics*, 34, 286–296.
- Beardsmore, G., Rybach, L., Blackwell, D., Baron, C. (2010). A Protocol for estimating and mapping the global EGS potential. *Proc. Australian Geothermal Conference 2010*, pp. 257-262
- Bertani, R., Thain, I. (2002). Geothermal power generating plant CO₂ emission survey. *IGA News* 49, 1–3.
- Bloomfield, K. K., Moore, J. N., Neilson, R. N. (2003). Geothermal energy reduces greenhouse gases. *Geothermal Resources Council Bulletin*, 32, 77–79.
- IEA, (2012). CO₂ Emissions from Fuel Combustion – Highlights. International Energy Agency, IEA (Edition 2012).
- Frick, S, van Wees, J.D., Kaltschmitt, M., Schröder, G. (2010). Economic performance and environmental assessment, in *Enhanced Geothermal Energy Systems, Geothermal Technology for Resource Assessment, Exploration, Field Development, and Utilization* (ed. E. Huenges), John Wiley & Sons, Ltd, in press.
- Fridleifsson, I.B., Bertani, R., Huenges, E., Lund, J. W., Ragnarsson, A., Rybach, L. (2008). The possible role and contribution of geothermal energy to the mitigation of climate change, in *IPCC Scoping Meeting on Renewable Energy Sources, Proceedings* (eds O. Hohmeyer and T. Trittin), Lübeck, January 20–25, 2008, pp. 59–80.
- Goldstein, B., Hiriart, G., Bertani, R., Bromley, C., Gutierrez-Negrin, L., Huenges, E., Muraoka, H., Ragnarsson, A., Tester, J., Zui, V. (2011). Geothermal Energy. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlomer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Holm, A., Jennejohn, D., Blodgett, L., GEA (2012). Geothermal Energy and Greenhouse Gas Emissions, Geothermal Energy Association, Report November 2012, http://geo-energy.org/reports/GeothermalGreenhouseEmissionsNov2012GEA_web.pdf.
- Moomaw, W., P. Burgherr, G. Heath, M. Lenzen, J. Nyboer, Verbruggen, A. (2011). Annex II: Methodology. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlomer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Nolasco, L. A. F. (2010). Hydrogen sulphide abatement during discharge of geothermal steam from well pads: a case study of well PAD TR-18, El Salvador. *Reports 2010*, 13, Geothermal Training Programme, Iceland.
- Sathaye, J., O. Lucon, A. Rahman, J. Christensen, F. Denton, J. Fujino, G. Heath, S. Kadner, M. Mirza, H. Rudnick, A. Schlaepfer, A. Shmakin, (2011). *Renewable Energy in the Context of Sustainable*

Development. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlomer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Stefansson, V. (2005). World geothermal assessment. In: *Proceedings World Geothermal Congress 2005*, Antalya, Turkey, 24-29 April 2005 (ISBN: 9759833204). Available at: www.geothermal-energy.org/pdf/IGAstandard/WGC/2005/0001.pdf.