Annual Monitoring Report

YEAR 2021/2022 – July 2022

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Deep GEOTHERMAL IWG
SUPPORT UNIT

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Contents

Introduction

This document represents the third Annual monitoring report, outlining the reported data in 2021 and first semester 2022. The first report (D6.6) was published in June 2020. It highlighted the key performance indicators (KPIs) established by the IWG for the year 2019, presented in D6.5. These KPIs are then updated every year. EGEC is in charge of overseeing the monitoring of KPIs that were established in the report D6.5. The SU-DG-IWG partners, together with the members of the IWG, evaluate and monitor the learning curve of the different geothermal technologies through reference assets and plants. Therefore, this third monitoring report is related to the reference plants, assets and to the 2019 value as a starting point in terms of costs.

A geothermal heat plant typically needs 5 years to become operational. For electricity, it takes between 6 to 8 years. Considering the above-mentioned timeline, this report is not able to present a full costs comparison between 2021 and 2022.

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Status	**Under Investigation**	**Under Development**					**In Operation**		
Prefeasibility	Services								
Exploration			Exploration & test drilling						
Resource development					Drilling				

Considering this, the **main objective is to establish new mechanisms to monitor the RD&I activities** set by the Deep Geothermal Implementation Plan and start the monitoring process. The first mechanism proposed in this report is to make a comparison of the costs in a specific country - the Netherlands.

Secondly, the report presents a series of case studies for presenting the main innovative demonstration projects of 2021-2022 and their potential impacts.

The third instrument is to update the perspectives for the execution of the implementation plan on Deep Geothermal.

The impacts of RD&I projects are defined by quantified smart performance indicators referred as reference plants and assets. The final objective of the data analysis presented in this report is to support and facilitate the work of the IWG by providing an understanding of the current trends in RD&I and to adopt corrective implementation measures if needed.

MONITORING BASELINE

The DG-IWG decided to have as baseline the date of endorsement of the Implementation Plan by the SET Plan Steering Committee – **24 January 2018**.

The first costs data correspond to the year 2019 and were reported mid-2020 in D6.6, following the adoption of the reference plants and assets in D6.5. This cost data has been updated annually; cost updates from 2020 reported in D6.7, and cost updates for 2021/2022 presented in this report, D6.8.

Key Performance Indicators

The reference assets are used to assess progress against the targets of the implementation plan of the SET-Plan's action on deep geothermal energy, which is one of a series of technologies that have been identified in two actions, whose purpose is to position Europe as "No. 1 in Renewables". Those actions are:

(1) to sustain technological leadership by developing highly performant renewable technologies and their integration in the EU's energy system and

(2) to reduce the cost of key technologies.

The Deep Geothermal Implementation Plan has 8 research and innovation activities, as well as 2 activities on non-technical barriers and enablers that serve to address the targets of the Declaration of Intent.

The indicators refer to both: geothermal power and/or heat plants and key assets.

Six plants are considered: three for power production (including one on EGS), and three plants for heat supply (including one combined heat & power system):

- 20 MW_e high temperature plant (Flash turbine)
- 10 MW_e medium temperature plant (Binary turbine)
- 5 MW_e electric EGS plant (or thermal EGS plant with a capacity of 25 MW_{th})
- 10 MW_{th} heating plant
- 10 MW_{th} heating plant assisted with large heat pumps
- 5 MW_e and 20 MW_{th} CHP plant

A series of assets are presented in the first report. The following reports do not only update the costs data, but also add new assets which are becoming relevant by technological development.

REFERENCE PLANTS

The choice of reference plants was defined to specifically address **the challenges highlighted in the Implementation Plan's target,** namely to *"Reduce production costs of geothermal energy (including from unconventional resources, EGS, and/or from hybrid solutions which couple geothermal with other renewable energy sources) to below 10 €ct/kWhe for electricity and 5 €ct/kWh$_{th}$ for heat by 2025".*[1]

For each plant category, the reference plant has been taken from the costs of plants in operation. The source is often from a basket of plants in a developed area, for example:

- 20 MW$_e$ high temperature plant (Flash turbine): example of some plants installed in **Tuscany, Italy**
- 10 MW$_e$ medium temperature plant (Binary turbine): extrapolation from the current plants (3-5 MWe) installed in **Bavaria, Germany**
- 5 MW$_e$ electric EGS plant (or thermal EGS plant): extrapolation from the current plants (1-3 Mwe, 24 MWth) installed in **Alsace, France**
- 10 MW$_{th}$ heating plant: example of some plants installed in **Paris region Ile-de-France, France**
- 10 MW$_{th}$ heating plant assisted with large heat pumps: example of some plants installed in **France and in the Netherlands**
- 5 MW$_e$ and 20 MW$_{th}$ CHP plant: example of some plants installed in **Bavaria, Germany**

The costs of geothermal plants depend notably upon economies of scale. The levelized cost of electricity decreases with an increase in installed plant capacity. In general, economies of scale allow both, unit capital cost (in Euros/kW installed) and unit operating and maintenance cost (in Euros/kWh produced) to decline with increased installed capacity.

The power plant construction includes the following steps:

1. power plant equipments: for example the costs for a 10 MWe medium temperature plant (Binary turbine) is between €15 - 25 million;
2. power plant installation and infrastructure (civil works, connection to grid ect.): in this case it would be around €15 – 20 million;

[1] SET Plan - Declaration of intent on Strategic Targets in the context of an Initiative for Global Leadership in Deep Geothermal Energy, https://setis.ec.europa.eu/system/files/integrated_set-plan/declaration_of_intent_geoth_0.pdf

System boundaries & clarifications

We do not consider the impact of energy storage or other system services that geothermal plants may provide, as there are insufficient examples and reported costs to give a sufficiently detailed picture. Storage of electricity produced by geothermal power plants is promising but not developed. Underground thermal energy storage associated to deep geothermal plants is still in the early stages of deployment.

Our reference plants have the following system boundaries:

- From project development until generation,
- We do not consider the transportation/transmission and distribution costs and benefits e.g. electricity distribution and DH infrastructure.

The expected lifetime of wells is more than 50 years. Overall, the useful lifetime of a plant is 25-30 years.

The weighted average cost of capital or the discount rate is fixed at 5%, for a period of 20 years. Wells or plants may not be fully depreciated but for our purposes, the residual value in the cash flow tail is of secondary importance.

Heat plant

For a geothermal heat plant, we assume that a plant will supply heat to a district heating network, to nearby greenhouses and agricultural businesses, or process heat to nearby industrial customers. Our reference plant is a geothermal doublet system accessing a reservoir at a depth between 2000-3000 m and a production temperature of around 80 °C. Operational hours range from 3800 to 6000 hours annually

Power plant

For the power plant, the reference plant has at least two wells to a depth between 2500-5000 m and a reservoir temperature in excess of 150 °C. Operational hours range from 6000-8000 annually.

Cost structure

Exploration and adaptation of a given technology to an unexplored geological context, presenting a higher degree of risk than in commonly known and well-understood areas, and possibly the ambient temperature, are key concerns and cost drivers for geothermal projects. Geothermal energy projects require substantial up-front investments and from the investor’s point of view long time horizons before a venture becomes profitable. Furthermore, drilling and exploration may take several years, and 3 to 6 years can pass between exploration and first production, with the cumulative cash-flow becoming positive quite a number of years after production has commenced.

Overall, unit costs for installed capacity for geothermal power generation per MW_e range between 1.8 to 10.6 million of euro (€ million) in Europe, and for heat generation about €1.2 and 2.9 million per MW_{th}; costs for the distribution systems excluded. Unit costs are higher than for virtually all other renewable energy technologies and depend highly on the specific site and technology chosen.

Capital costs depend strongly on the:

- Number of geothermal wells required;
- Depth of the reservoir, and hence drilling;
- Geological conditions;
- Location and access to drilling site(s) and size of the plant.

Figure 1 and *Figure **2**: Cost range for the development of a 10 MW $_e$ medium temperature plant with a binary turbine. The graph shows the cost range for the different steps in field development and the construction of the power plant.* show the breakdown of the capital cost for the different development stages for two types of geothermal power plants: a 20 MW$_e$ high temperature flash plant and a 10 MW$_e$ medium temperature binary plant. Figure **3***: Cost range for the development of a 5 MW $_e$ (or thermal 25 MWth) EGS plant. The graph shows the cost range for the different steps in field development and the construction of the power plant with a turbo-generator.* addresses a 5 MW$_e$ (or thermal) EGS plant (cost differences are attributable to the topside facilities such as those required for electricity generation (turbine, generator, substation and peripherals). Also, cost information is provided for a 10 MW$_{th}$ geothermal district heating (DH) plant utilizing a well doublet (Figure **4***: Cost range for the development of a 10 MWth geothermal DH (doublet) systems, producing 40.000 MWh/year (investment cost = €1.3-1.8 million/ MWth). Capital costs do not include costs for the installation of the district heating grid (about €1 million/km).*), a 10 MW$_{th}$ heating plant integrated with large heat pumps to maximize energy yield (Figure **5***: Cost range for the development of a 10 MWth geothermal DH (doublet) systems, assisted with two large heat pumps of 4 MWth.*), and a combined heat and power (CHP) plant with an installed capacity of 5 MWe and 20 MW$_{th}$ (Figure **6***: Cost range for the development of a 5 MW $_e$ and 20 MWth CHP plant (including a turbo-generator).*).

Typically, operators begin with screening of a potential resource, obtaining permits, extensive and detailed planning, and obtaining finance for the project; these costs vary from €1 to 10 million.

The next step encompasses exploration to better quantify the size of the resource and to define targets for (exploration) drilling. Exploration typically encompasses investigating surface manifestations, geophysical surveys and subsurface modelling, but may also include drilling of exploration well(s). Exploration costs range from €0 to 7 million (cost of drilling an exploration well is included within the drilling costs in the following stage) and are linked with the planning phase.

Once the resource has been outlined, the well field is designed and developed, adding another €20 to 40 million to the development (drilling) costs of a power project and €8 to 12.8 million on average for a geothermal heat project. Investing in exploration generally leads to a reduction of the subsurface unit technical cost because of higher certainty regarding the resource, its location/depth, spatial extent, location of inflow and outflow zones and so on. Hence, there is a relationship between exploration and field development phases and their respective costs.

The total subsurface development cost, prior to construction of the power plant amounts to around €23 to 47 million, and €9-16.8 million prior to construction of a heat plant. Until the well field has been developed, there is a risk of failure in connection with the expected subsurface geothermal resource and consequentially a substantial risk for financial loss. Also adding to the time until first power and heat, is the need to first develop the subsurface and obtain data that allows for the appropriate sizing of surface facilities, in particular the power or heat plant.

Depending on the capacity of the plant and the technology used, constructing the power plant will add another €9.1 to 50 million of capital expenditures, and €3 to 7 million for a heat plant. As mentioned, we do not include the cost related to transmission and distribution of, for example, a district heating network (about €1 million per km). Obviously, as both the field and plant have been constructed, the risk is mostly commercial and less governed by resource risks and hence has much more manageable financial consequences.

Costs associated with CHP plants have not been included in the above costs since cogeneration plants account for a small percentage of geothermal capacity installed in Europe; 20-25% of the total geothermal electricity generation capacity installed, and about 20% of the geothermal district heating and cooling capacity. The overwhelming majority of this capacity located in Iceland where geothermal is at the core of an integrated strategy for the provision of district heating.

In total, the development of a geothermal power project until first power requires an overall investment ranging from €77- 97 million for a 10 MW_e medium temperature, binary cycle power plant, €37.1 – 53 million for 5 MW_e EGS plant, and €36 – 66.5 million for a 20 MW_e conventional high temperature plant. Note that costs may vary substantially for a large number of reasons.

Although no cost update information was received from stakeholders specific to conventional high temperature plants using flash turbine technology, it was possible to update costs for 2021-2022 based on cost updates from stakeholders that were not stated as being specific to a particular reference plant/technology type, and according to 2021 renewable power generation costs from IRENA Renewable Power Generation Costs in 2021 (irena.org). According to IRENA, in 2021 the global weighted average total installed cost was USD 3 991/kW, equivalent to 3.9 million euros/MW. It is now rare to see projects with costs below 2 million euros /MW. This data is based on the global weighted average total installed cost, and therefore includes both binary plants and conventional high temperature plants which vary considerably in cost.

Typically, costs for binary plants designed to exploit lower temperature resources tend to be higher than those for direct steam and flash plants, as extracting the electricity from lower temperature resources is more capital intensive (IRENA, 2022). The updated costs for 2021 - 2022 reflect this relationship.

The development of a geothermal heat project until first heat costs between €12 and 21 million for a 10 MW_{th} plant size supplied by a well-doublet, to which, for reasons of maximizing efficiency of energy recovery one may add between €4.3 – 4.9 million for the large heat pump (of 4 MW_{th} capacity).

Costs for the development of a 5 MW_e and 20 MW_{th} CHP project (including topsides for power generation) range between €20.4 – 28.3 million.

The optimal capital expenditure profile very much depends on trade-offs and probability of success for each of the phases; exploration, development, and power/heat plant construction. One must not add the maximum of each phase to arrive at a cost estimate for a geothermal energy project; each phase influences the cost for the subsequent phase. For example, a more extensive, and hence expensive, exploration phase may pay back through reduced unit drilling cost because the probability of a successful well increases, planning and design of wells is improved, and the likelihood of costly operational and technical interventions is lowered because of improved knowledge.

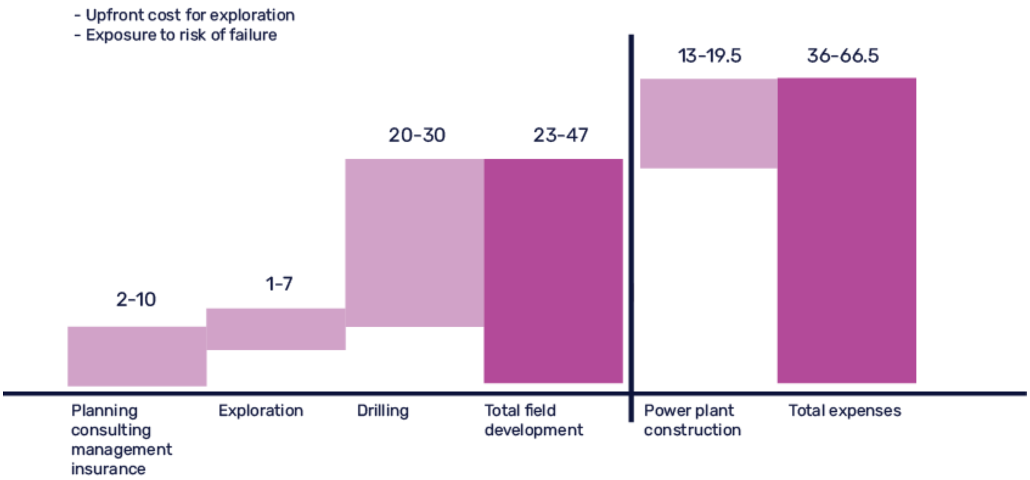


Figure 1: *Cost range for the development of a 20 MW_e conventional high temperature plant with a flash turbine. The graph shows the cost range for the different steps in field deveolopment and the construction of the power plant.*

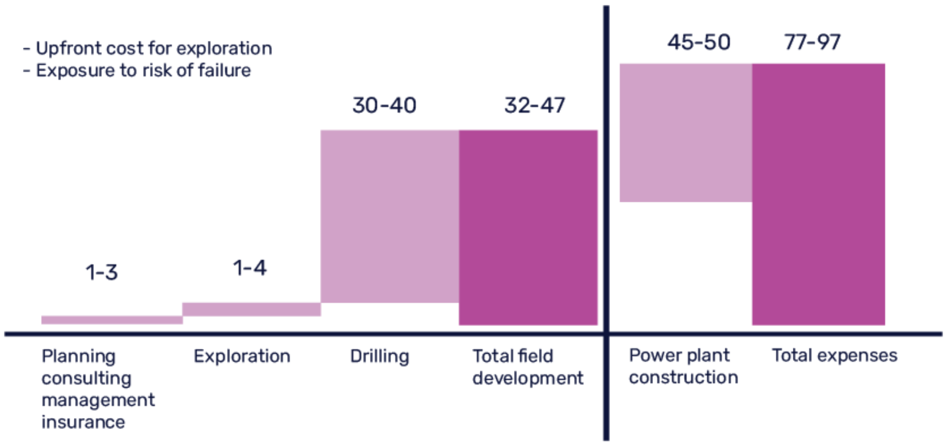


Figure 2: *Cost range for the development of a 10 MW$_e$ medium temperature plant with a binary turbine. The graph shows the cost range for the different steps in field development and the construction of the power plant.*

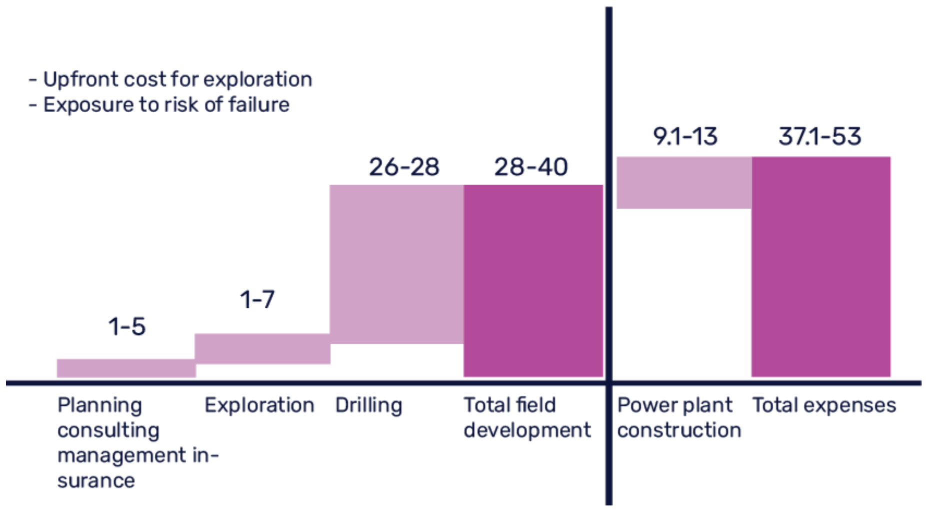


Figure 3: *Cost range for the development of a 5 MW$_e$ (or thermal 25 MW$_{th}$) EGS plant. The graph shows the cost range for the different steps in field development and the construction of the power plant with a turbo-generator.*

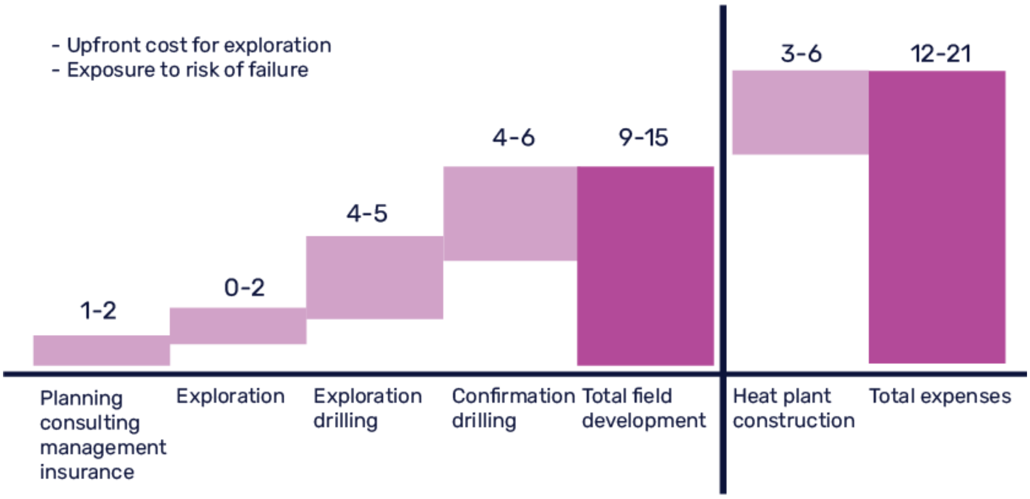


Figure 4: *Cost range for the development of a 10 MW_{th} geothermal DH (doublet) systems, producing 40.000 MWh/year (investment cost = €1.3-1.8 million/ MW_{th}). Capital costs do not include costs for the installation of the district heating grid (about €1 million/km).*

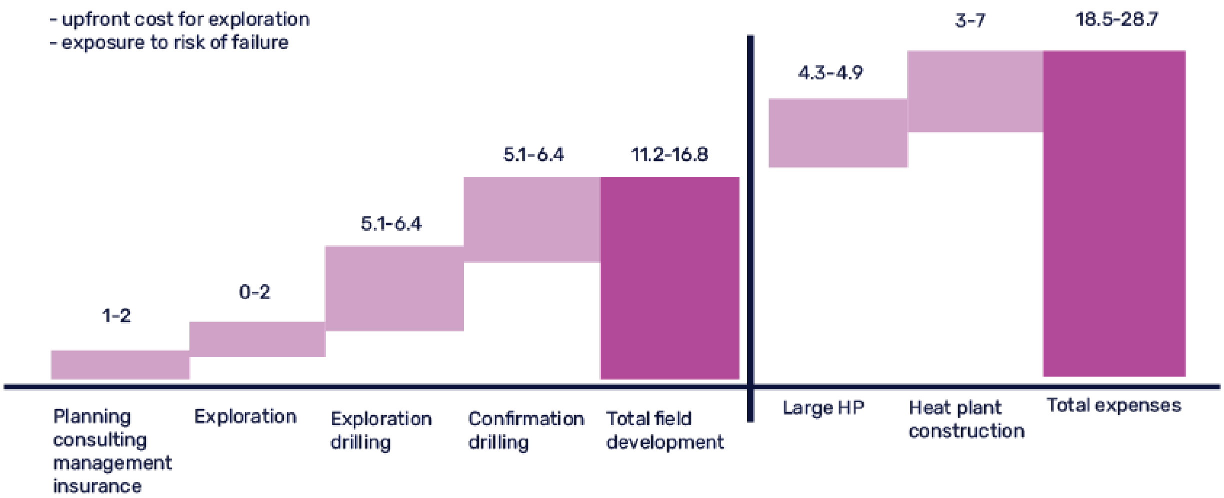


Figure 5: *Cost range for the development of a 10 MW_{th} geothermal DH (doublet) systems, assisted with two large heat pumps of 4 MW_{th}.*

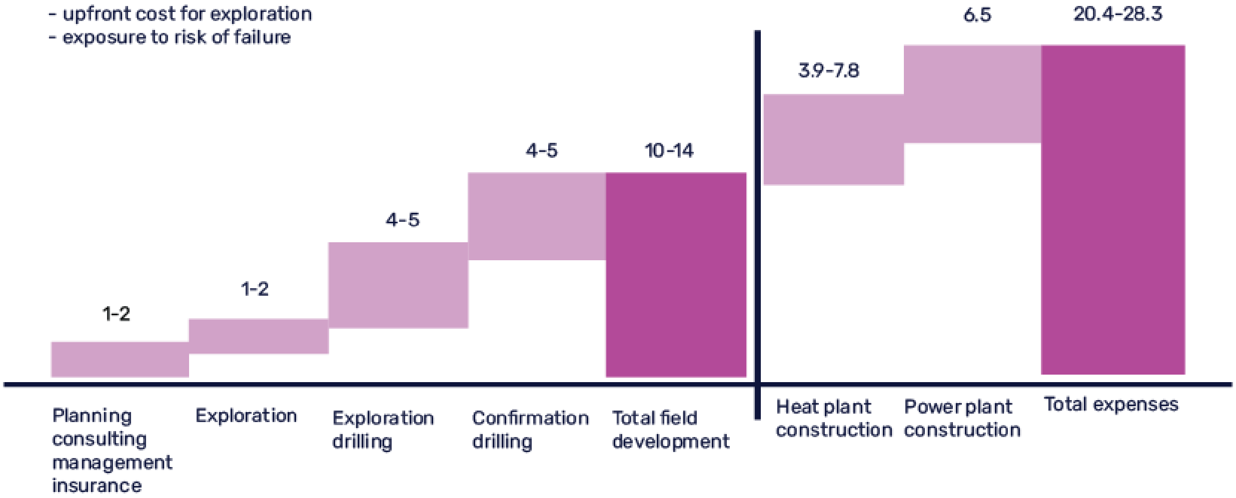


Figure 6: *Cost range for the development of a 5 MW$_e$ and 20 MW$_{th}$ CHP plant (including a turbo-generator).*

The ultimate profitability of geothermal energy projects strongly depends on the weighted average cost of capital. Generally, the cost of capital for investors in risky ventures is higher than for de-risked and predictable ventures. Geothermal energy projects are not only capital intensive, but also require significant up-front investments to de-risk a venture until parameters of the resource, and hence possible revenue streams, can be quantified. Regarding the above figures, the high-risk stage corresponds to expenditures for resource identification and exploration and exploratory drilling. In the case of projects requiring stimulation or reservoir engineering, there is significant uncertainty on the potential capacity and output of the project until this task has been successfully completed. This means that between 40 and 75% of a geothermal project cost must be invested when there is a very high level of uncertainty regarding the success of the development. This usually translates in higher costs of capital and challenges to find investors with an appropriate risk appetite; typical investors in subsurface energy projects (such as oil and gas) are used to high returns on risky investments.

2022 costs			
Plants	Capital Costs	Production Costs	Clarifications
20 MW_e high temperature plant (Flash turbine)	€36 – 66.5 million in total	38/52 €/MWh_e[2]	€1.8 - 3.3 million/ MW_e Power plant construction: turnkey costs for Utilities in Italy and Iceland
10 MW_e medium temperature plant (Binary turbine)	€77-97 million in total	140-180 €/MWh_e	€7.7- 9.7 million/ MW_e Costs will vary according to the increased amount for power plant construction and installation.
5 MW electric EGS plant (or thermal 25 MW_{th})	€37.1 - 53 million in total	Not available	€7.42 -10.6 million/ MW_e 1. power plant equipment: €10 – 15 million 2. power plant installation and infrastructure (civil works, connection to grid ect.): € 10 – 15 million
10 MW_{th} heating plant	€12-21 million in total	15 to 70 €/MWh [3] &[5]	€1.2 – 2.1 million/ MW_{th}
10 MW_{th} heating plant assisted with heat pumps	€18.5 – 28.7 million in total	15 to 70 €/MWh [5]	€1.85-2.87 million/ MW_{th}
5 MW_e and 20 MW_{th} CHP plant	€20.4 – 28.3 million in total		CHP costs: 1. power plant equipment: €10 – 15 million 2. power plant installation and infrastructure (civil works, connection to grid ect.): € 10 – 15 million

[2] International Renewable Energy Agency, *Geothermal Power Technology Brief (2017),* https://www.irena.org/publications/2017/Aug/Geothermal-power-Technology-brief#:~:text=August%202017&text=Geothermal%20power%20is%20generated%20from,of%20solar%20and%20wind%20power.

[3] ADEME, *Costs of Renewables and recovered heat in France (2020*), https://www.ademe.fr/cost-of-renewable-and-recovered-energy-in-france

[4] ademe_couts-energies-renouvelables-et-recuperation-donnees2022-011599.pdf (geothermies.fr)

[5] New geothermal heating project to kick off in greater Paris (thinkgeoenergy.com)

Costs of reference plants have been updated for the period 2021-2022 according to feedback from a range of stakeholders, based on their observations between the reporting period 2021-2022, working on operational plants in the developed areas stated for each reference plant.

The year 2021 saw a significant rise in inflation across the world as a result of Covid-19 pandemic related supply chain issues, and rising energy prices. This energy price crisis has continued, and with greater intensity, in 2022, raising a number of questions regarding the capacity of the geothermal sector to access the services and equipment necessary for project development. The war in Ukraine has further exacerbated inflation, with the threat of supply and turbulence in the energy market causing energy prices to spike.

It is already a very clear perspective that the costs of many equipment and services will increase following the tremendous inflationary pressures on all segments of the supply chains, including raw materials. Geothermal developers, who often use similar service companies and equipment to the oil and gas industry, will also be facing the renewed interest into developing new oil and gas projects after several years of lower hydrocarbon prices, and the significant pressure to secure alternative oil and gas supplies following Russia's war on Ukraine.

As reference, the index price of REBAR steel in Europe for instance increased from a 266.5 in January 2021 to 338.8 in November 2021, with a peak during the year of 349.9 in August. The same is true for all steel products, which saw their demand increase rapidly as several industrial sectors started operation anew simultaneously following the pandemic. For various steel products, price increases during 2021 ranged from 27% to 50%.

For stainless steels, which are essential for the manufacturing of many components in geothermal power plants, including in some cases well casing or turbine blades, the price increase was even starker, with price increases ranging from 52% to nearly 70% according to the products. This is notably driven by price increases in the crucial materials necessary to manufacture stainless steel such as chromium (nearly doubling in the year), molybdenum (prices doubling over the year) or nickel.

Furthermore, Ukraine and Russia represent well over a third of steel supply to Europe, including for dedicated steel products suitable to geothermal power plant construction including steel tube casing for geothermal wells. We can therefore expect prices to remain high throughout 2022.

Stakeholders reported increased costs of resources including steel, copper and aluminium, and scarcity of drilling support infrastructure. Moreover, increased cost of raw materials is raising the commodity prices of power plants. One stakeholder reports a 10-15% increase to the cost of OCR power plants, compared to 2019 costs. Another reports a 30% increase in cost of power plants compared to the period 2020-2021 and suggests that it could be expected that the unit cost will increase but only in line with other industries.

IRENA’s cost analysis programme for 2021 concluded that not all of the materials cost increases witnessed to date have been passed through into equipment prices. This suggests that price pressures in 2022 will be more pronounced than in 2021 and total installed costs are likely to rise this year in more markets. This data and analysis is based on the IRENA Renewable Cost Database that has data on around 21 000 renewable power generation projects from around the world.

REFERENCE ASSETS

The reference assets are used to assess progress against the targets of the implementation plan of the SET-Plan’s action on deep geothermal energy, which is one of a number of technologies that have been identified in two Actions whose purpose it is to position Europe as “No. 1 in Renewables”. Those actions are (1) to sustain technological leadership by developing highly performant renewable technologies and their integration in the EU's energy system and (2) to reduce the cost of key technologies. The Deep Geothermal Implementation Plan has 8 research and innovation activities as well as 2 activities on non-technical barriers and enablers that serve to address the targets of the declaration of intent. The research and innovation activities are expected to yield concrete steps in the field of:

1. Artificial lift technologies (such as pumps in production wells) that will result in an increase reservoir performance by lowering the power demand for plant operations to below 10% of gross energy generation by 2030;

2. Development in turbine technologies are expected to improve the overall energy conversion efficiency, including efficiency gains in the bottoming cycle of geothermal installations at different thermodynamic conditions by 10% in 2030 and 20% in 2050;

3. The development of exploration tools that will reduce the unit finding cost (€ per potential capacity of a geothermal reservoir) by 25% in 2025, and by 50% in 2050 compared to 2015. The reduction in unit finding cost not only covers methods and tools that deliver improved reservoir definition prior to drilling but an increase of the probability of success for exploration wells;

4. Advances in drilling technologies are expected to reduce the unit cost (€/MWh) of a well’s thermal output by 15% in 2020, 30% in 2030 and by 50% in 2050 compared to 2015;

5. Advances in geothermal power flexibility will enable geothermal plant operators to develop additional revenue streams resulting from the grid operator’s need to improve

reliability and stability, specifically geothermal power plant operators may demonstrate the feasibility of fast output ramp-up and -down between 60% - 110% of nominal power.

For the purposes of the development of KPIs for the Deep Geothermal Implementation Plan (the 8 research and innovation activities), **“assets” are defined as any activity that has the potential to help deliver the targets of the Deep Geothermal Declaration of Intent and specifically - the cost targets.**
These activities have economic and commercial value and hence are characterized as “assets”.

Few inputs were received regarding the costs of the defined assets for the reporting period 2021-2022. Therefore, presented below are the 2020 costs of defined assets, with the exception of large heat pumps of 4 MWth, routing and cable installation, and district heating grids which have been updated to reflect a 20-25% increase in cost of surface equipment, attributable to post Covid-19 and war speculation on the market, according to feedback from a stakeholder based on operational heating plants in France.

2022 costs (updates)			
Assets	**Capital Costs**	**Comments**	
Average costs for identifying a resource	€350,000 and €1,000,000	costs of exploratory drilling is excluded	While many of the assets that constitute value of exploration techniques are low cost, the costs for 2D & 3D seismic surveys and sophisticated modelling tools may be substantial.
Cost estimates for resource exploration	€1-10 million	for the full exploration phase	
Drilling costs to a depth of 1800 m and rate of penetration (hole-making) of 5-10 m per hour	€5.1 million per well	for a typical heat plant	

Downhole pumps: ESP	€180,000 - €300,000	Investment costs for selecting and installing an ESP	
Yearly operational costs	€60,000 - €100,000	without including the electricity costs for driving the pump.	
Piping and controls for steam gathering	€80,000 - 200,000	steam gathering system of a high temperature flash system can exceed €300/kWe once installed	
Heat exchanger	€130,000 – 150,000	For a typical heat plant most expensive positions are manufacturing (welding, machining, assembling…) and the acquisition of tubes and sheet plates	
Large Heat Pumps of 4 MW_{th}	€4.3 – 4.9 million		
Transfer station of a 1 MW_e power plant	€80,000 - €85,000		
Routing and cable installation	€122.5-183.8 per meter		
District heating grid	€1.2 million/km	On average	

LEARNING CURVE IN 2022

Review from the Netherlands

At the request of the Netherlands Ministry of Economic Affairs and Climate Policy (EZK), PBL (Netherlands Environmental Assessment Agency) issued the draft advice on the opening of SDE++ 2022. PBL issues advice on base amounts, correction amounts, base energy prices and financial-economic parameters related to this. The document contains the draft advice for geothermal energy SDE++ 2022 which provides an update of the overview of costs and other parameters of geothermal projects. This cost information is presented below.

Stimulation of Sustainable Energy Production is a Feed in premium scheme for sustainable energy in the Netherlands.

The Geothermal heat production categories in 2022 are:
• 'Shallow' ≈ 500-1500 m depth
• 'Deep' ≈ 1500-4000 m depth
• 'Ultradeep' > ≈ 4000 m depth

The Base reference cost is adjusted annually by the PBL, TNO and DNV-GL. This is based on cost data of actual plants.

Reference to the SDE+, link to 2022 document Conceptadvies SDE++ 2022 Geothermie (pbl.nl)

CAPEX and OPEXare based on 57 projects in the Netherlands.
For these cost findings, only projects within the category Deep geothermal (base load) are examined. The drilling depth of most projects is between 2000 and 3000 meters. The various geothermal projects are classified as follows for the analysis made:

• in production, 22 projects
• not yet in production (already realized), 2 projects
• not in production (requested), 33 projects.

These numbers deviate from what TNO AGE reports for the annual report to the ministry of Economic Affairs and Climate, because the analysis only considers 452 projects for which an unambiguous and complete dataset is available.

CAPEX

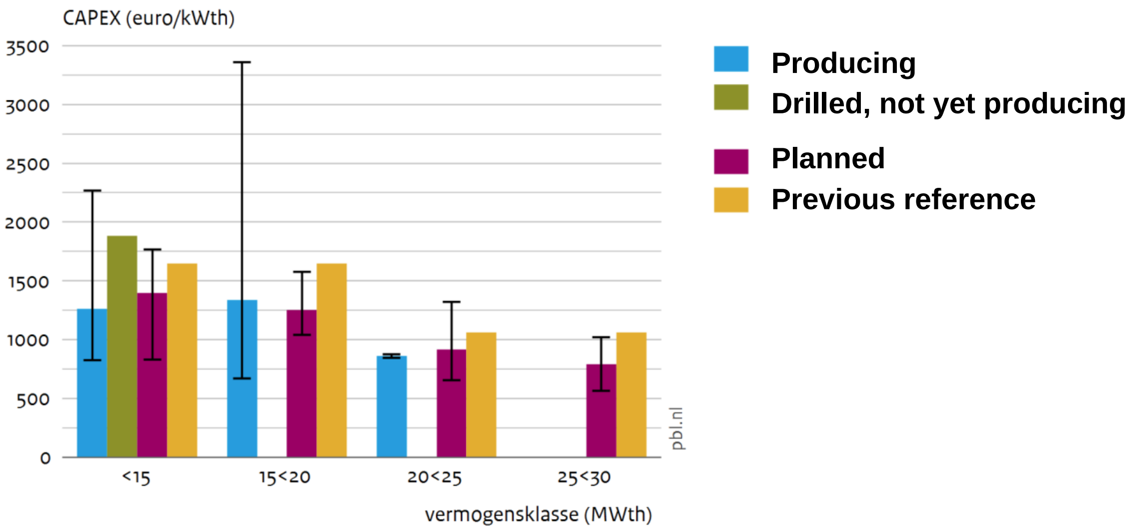


Figure 7: Specific investment costs, based on source capital. (Source power is corrected on the one hand for projects that are not yet producing, on the other hand the maximum power that has been achieved is taken for projects already producing). Source: PBL

Cost structure CAPEX

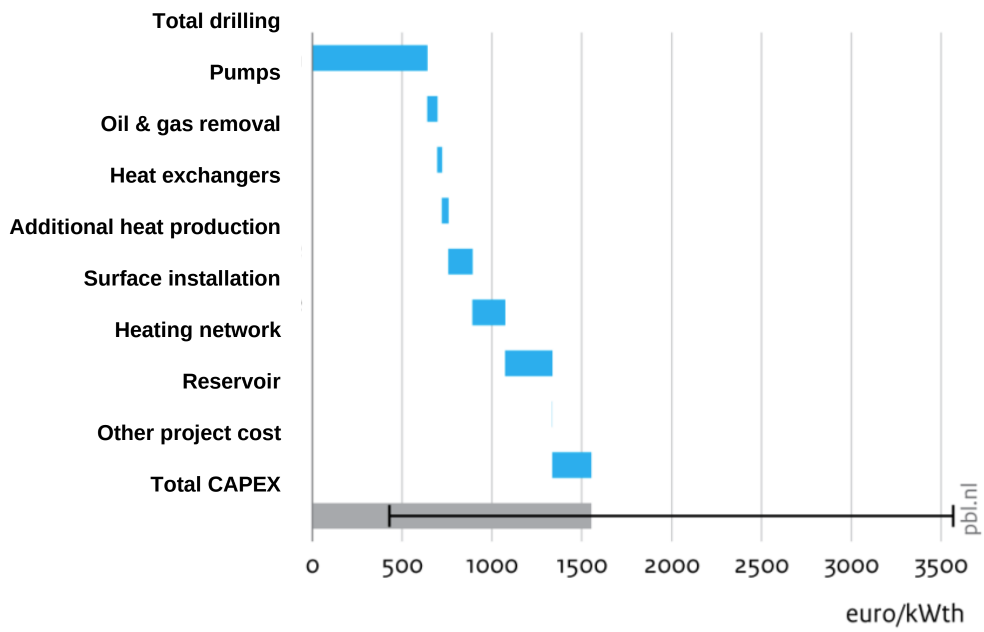


Figure 8: Representation of the structure of the average composition of the investment costs in over the various analysed projects. The spread on the total provides insight into the total spread over the analysed projects. Source: PBL

OPEX

The projects considered in the cost-finding study do not distinguish between fixed and variable costs, showing operating costs (OPEX) only as annual cost per kWth.

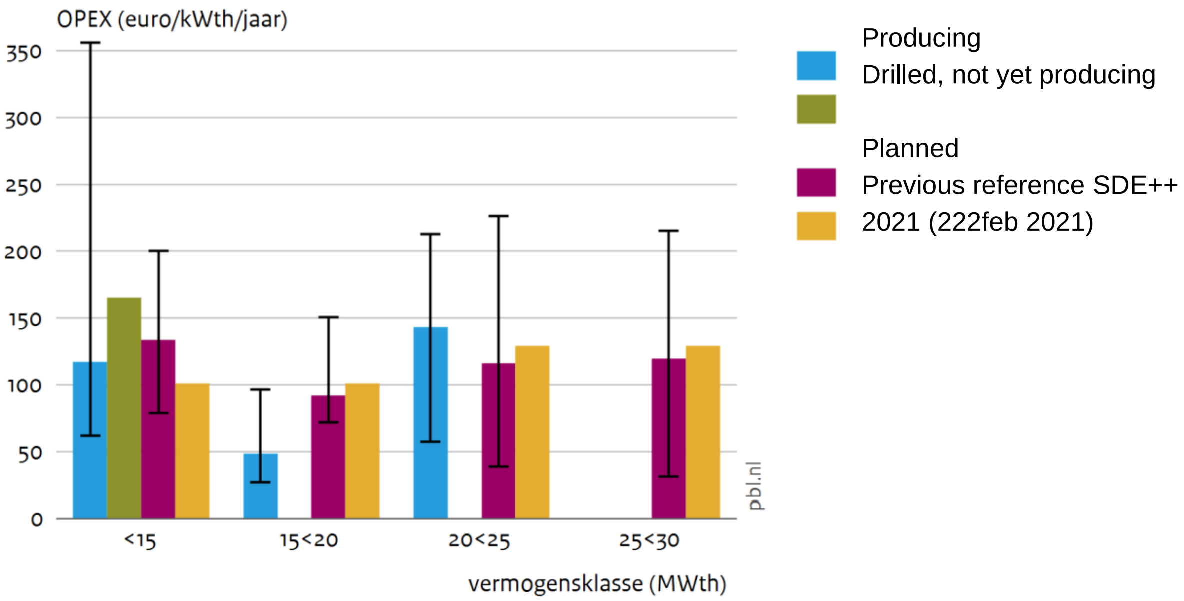


Figure 9 shows the average composition of the OPEX from the cost survey, divided over the various projects.

Cost structure OPEX

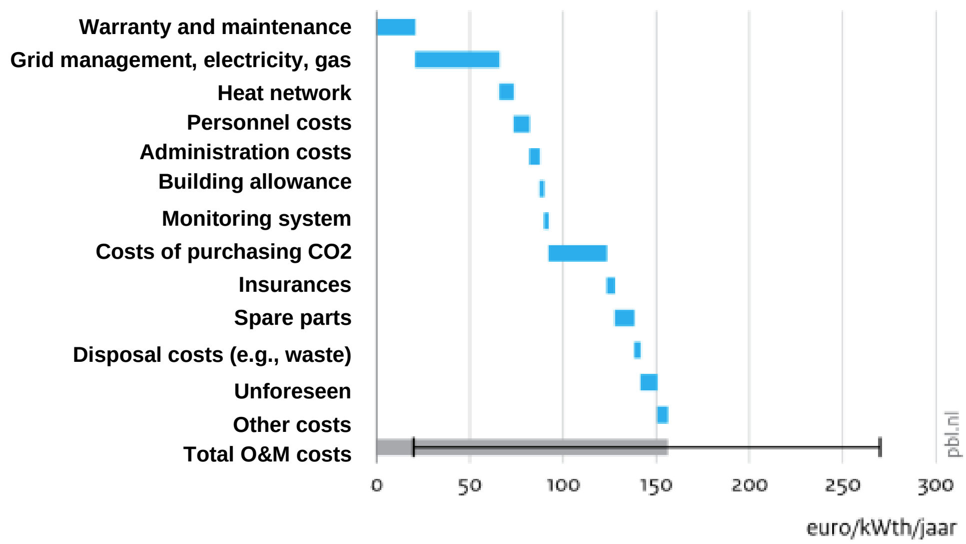


Figure 10 Representation of the composition of the average composition of the OPEX on the different projects analysed. The spread on the total provides insight into the total spread over the analysed projects. Source: PB

Case studies

The following case studies aim to report the impact on cost reduction or improvement in efficiency for the reference plants.

Case study 1: Geothermal district heating project in Velizy-Villacoublay (France)

Drilling operations started in September 2020 for a new geothermal district heating network in Velizy-Villacoublay (France). The project developed by ENGIE aimed at covering more than 60% of the heat demand for this city.

The project received a financial public support from the Region Ile de France and the ADEME for around €9 million. The expected **GHG emissions savings were about 22 800 tCO2/year.** Moreover, the rig used to drill was running 100% with electrical power (first time in Paris Basins), which means around 5 500 tCO2 saved.

The **innovation part** of this project consisted in the wellbore design in order to deal with a thin geothermal reservoir. The bores' true depth is around 1600 m, while the total measured depth reached **2400 m thanks to the innovative MultiDrains**. This method has been already used in other sectors, such as oil&gas, but in this case, it was the first time that it has applied for a geothermal energy project.
Instead of the conventional deviated bores with 30° to 40° angle and one single drain, the bores in Velizy-Villacoublay were drilled vertically on 400 meters and were then deviated at 65°- the deviation increased until it has reached the 'U' shape. This method allowed to cross twice the Dogger reservoir and increase the exchange surface.

At the top of the deviation, the MultiDrains technology is applied to multiply the captations. The bores architecture is composed of 3 drains, which allows to cross multiple time the reservoir and thus to increase the final productivity in the following steps:

- The first drain taps the reservoir at the end of the first drilling path;
- The second one taps the reservoir a bit further considering an optimised spacing between the first drain and the second drilling path;
- The third one starts from the end of the first path to go down the reservoir vertically and create a sedimentation pocket.

As a result, the flow rate is increased with the objective to reach a minimum of 350 m3/h. Such a new technology, entirely developed by the company ENGIE, has an extra cost of 15% to 20% in comparison with a traditional drilling, but the expected gain on the flow rate reaches around 30. The temperature is around 64°C and the system will be assisted by heat pumps.

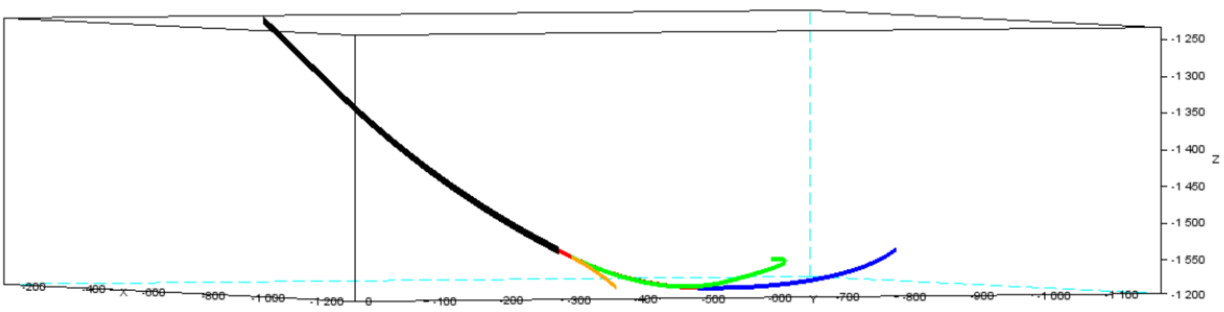
In December 2021, the geothermal heating plant at Vélizy-Villacoublay, France was officially inaugurated bringing significant savings to local district heating customers.

As of 9th December 2021, the [price of MWh thermal] goes from EUR 125 to EUR 93. Residents will save 25% on their heating bill from December. For a family of five, this represents EUR 500 in savings per year.

The geothermal heating systems will provide heat to 12 000 eq. housings and the heat capacity is evaluated at 16 MWth. The **total investment costs are €25 million**. A capital cost of €1.56 million/MWth can be deducted.

In conclusion, this innovative project in Velizy-Villacoublay broadens the field of possibilities for hot sedimentary aquifers exploitation: for a long time many areas that are considered to have low geothermal potential due to the poor reservoir quality, are becoming now the **new potential targets for geothermal district heating.**

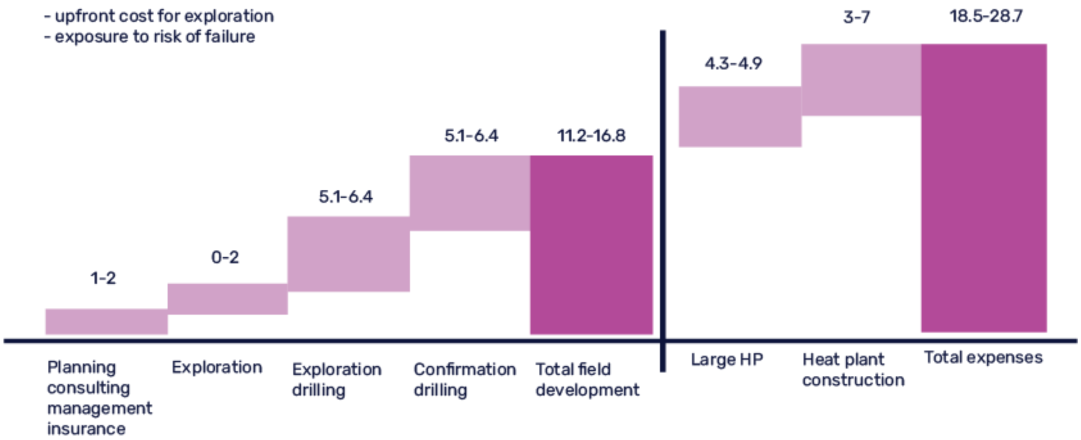
Figure 11*:* Diagram of the innovation with two drains (also called the crow's feet)



Source: ENGIE, 2020 (https://www.engie-solutions.com/fr/actualites/veligeo-velizy-villacoublay)

Project Véligéo:	• 1 600 m: Wells depth • 2 400 m: Wells length • 16 MW: Capacity
DH in Vélizy:	• 19 km • 140 supply points • 12 000 eq. inhabitants • 130 MW installed capacity
Work Plan:	• July to August 2020: Construction for pre-drilling • August 2020 – Winter 2021: Drilling operations • 2021: DH plant construction and connection to the network • End 2021: Test and start of the operation • December 2021: Geothermal plant was officially inaugurated

Figure 12: *:* Comparison of Cost range for the development of a geothermal DH (doublet) systems, assisted with two large heat pumps, between the reference plant and the plant in Velizy



Case Study 2: Bobigny and Drancy heating systems

Since 2018, Sipperec has been conducting a drilling project in Bobigny and Drancy to supply a heating network in these municipalities.

After a series of tests and verifications, on the evening of March 10th 2021, the system became operational and the first MWh of geothermal energy left the grid.

Drilling works were carried out continuously 24 hours a day for 307 days, and targeted the Triassic aquifer at 2100m, beyond the Dogger Aquifer at 1600m where geothermal drilling is normally targeted. Four wells were drilled, each to more than 2000m long.

The operation of the Triassic is a technological innovation, successful for the first time in France, and will open up new horizons in terms of geothermal energy. Today, two thirds of the Ile-de-France wells are concentrated in the east, south and north. The success of this project will allow exploration in the west of the Ile-de-France region, where the water extracted from the dogger does not reach a sufficient temperature to be exploited.
The water is naturally warmer when it comes from the Triassic – at 80 degrees against 60 – the operating costs will therefore be lower.
The cost of deeper drilling is obviously higher: going down in the Triassic amounts to 9 million euros per well compared to 5 million for those that stop in the Dogger. However, according to Sipperec, the price charged to network users could even be reduced.

All subscribers now benefit from this renewable, local and competitive resource compared to fossil fuels. Geothermal energy provides subscribers with a controlled cost over time, as well as a VAT reduced to 5.5% on all invoices.

Additional work was then carried out at the boiler room of the historic Bobigny heating network in order to convert the existing installations initially running on gas and oil to this renewable energy.

Work began in 2020 and until September 2021 to renovate and extend the heating network over 30 km, thus finally allowing 20,000 housing equivalents to benefit from geothermal energy (collective housing, public buildings, sports facilities, etc.).

With more than 60% geothermal energy, the Gényo heating network will avoid the emission of nearly 30,000 tons of CO_2 every year.

The total investment of the Gényo project amounts to €70.5 million. This project is made possible thanks to the European Regional Development Fund (ERDF), ADEME and the Region's call for renewable heat projects. The Ile-de-France Region has awarded €4 million in aid and ADEME has contributed €16.9 million to the project under the Heat Fund. Sipperec brings almost 50 million.

Case Study 3: Innovative Combined heat and power plant in Germany

In early 2022, the city councillors of Geretstried in Bavaria, in the South of Germany, approved the planning permit for a geothermal power plant to be developed using a closed-loop system approach by Canadian Eavor Technologies. The decision to deploy the Eavor-Loop technology for this project was made about two years prior.
This new approach follows two unsuccessful drilling campaigns in 2013 and 2017.
Eavor have selected Turboden S.p.A. (Turboden) and its Organic Rankine Cycle ("ORC") system for the development of the geothermal power project.
The facility is being built in the forest near the Breitenbach estate, 2.5 kilometers south of Gelting and 3.5 kilometers west of Geretsried.
The project, will have a capacity of 8.2 MWe (4 loops and a single ORC generator) when it reaches its full capacity. The estimated date of initial power production is 2024 and the plant is expected to be operating at full capacity by 2026.
Eavor estimates 4,900 homes per Eavor-Loop will be powered with the geothermal energy. The full 8.2 MWe project will result in ~44,000 tCO2e GHG emissions avoided per year including anticipated heat offtake in addition to the power. Furthermore, Eavor estimates 150 drilling services and powerplant/infrastructure jobs will be created during the construction phase of the project.

The new technological approach by Eavor, known as the Eavor Loop, consists of a closed network of underground wellbores in which fluids circulate and are heated by the natural heat of the earth, as opposed to previous approaches which relied on permeability at depth for sufficient flow rate.
Eavor promotes the system as a scalable and “go anywhere” solution, unlocking a reliable and consistent energy source.
The first of the pipeline systems are to be built this year, at a depth of 4500m. Three more are expected by 2024.
Furthermore, Eavor are working with Huisman on the development of a new automated drilling technology that allows for the degree of precision – and speed – required to render this technology scalable.

Case Study 4: CHP in Pullach with new valves

Since 2005, the community of Pullach im Isartal, located in the south of the administrative district of Munich, has been operating a geothermal CHP plant run by Innovative Energie für Pullach GmbH (IEP GmbH).
The projects consists of two boreholes (doublet). Hot water with a temperature of 102° C to 107° C is conducted to the surface via the extraction borehole from a depth of about 3,500 m and fed into a heat exchanger. After running through the heat exchanger, the heated water is supplied directly to the consumers.
VAG equipped the geothermal energy plant with two VAG RIKO® Plunger Valves DN 150 PN 25. These two valves were installed between the wellheads and the heat exchanger, and another VAG RIKO® Plunger Valve DN 200 PN 25 was installed upstream of the re-injection borehole.
The control valves are custom-made plunger valves, made completely of special steel casting, and are resistant to temperatures of up to 150° C. The medium to be controlled by the valves contains high concentrations of soluble gases such as methane, nitrogen or carbon dioxide and has an operating temperature of 107° C. The valves keep the system pressure at a constant level so that all the dissolved gases remain dissolved to prevent any deposits.
Almost all public buildings, including the town hall, municipal hall, swimming pool and schools, and church institutions, commercial enterprises and private customers are supplied with heat generated in the plant. By 2011 Pullach’s district heating network had grown to 25 km.

Case Study 5: Digitalisation in Chiusdino geothermal plant

In Tuscany, geothermal accounts for 70% of all electricity from renewable sources and supplies over 34% of the region’s electricity demand. It also provides approximately 454 GWh of heating. This is equivalent to about 121,000 tons of CO2 emissions.

The power plant in Chiusdino, Tuscany, was built in 2011 and is part of the world's oldest geothermal complex, offering energy efficiency that brings environmental and economic benefits to the area and local communities. Geothermal steam is used as a primary heating source for the town through the district heating system, making the town completely carbon-free.
The Chiusdino plant has a 20-MW turbo generator set capable of generating up to 150 million kWh of energy per year, saving 31,000 metric tons of oil equivalent (toe). The turbine is powered by approximately 130 T/h of geothermal steam originating from four nearby wells.

District heating system

In 2019, the district heating system for the town of Chiusdino was completed using geothermal steam as a primary heating source for homes, shops and craft workshops.
With the second phase of the project, the town of Chiusdino has become completely carbon free, eliminating all emissions of CO_2 and fine particulate matter from boilers and stoves powered by fossil fuels. It is estimated that this will lead to 2,600 metric tons fewer CO_2 emissions a year, and avoid the importation of 1,000 TOE, with remarkable benefits in environmental terms. This is also an important example of circular economy, because thermal resources are a form of residual energy from the process that generates geothermal electricity.
District heating plants enable the reuse of residual heat for the benefit of the town's population, allowing people to save on their heating costs, while also serving as an incubator for the creation of new businesses that can benefit from the low cost of heat. Moreover, geothermal district heating boosts the value of local real estate, making houses healthier to live in and encouraging the use of properties that may have been abandoned otherwise.
This system of district heating is present in 10 municipalities that are home to geothermal plants, and provides heating to more than 10,000 residential users, contributing to a remarkable reduction in greenhouse gas emissions.

Innovative environmental technologies for sustainable production

The Chiusdino plant meets extremely high **environmental** standards: thanks to the multiple uses of its geothermal resources, it can be considered a model facility and is often used for educational events with schools, universities and companies.
The plant, like the other 33 in the Tuscan geothermal area, is equipped with a system to separate and clean steam and eliminate water, and with a mercury and hydrogen sulfide emissions abatement system (with Enel's proprietary AMIS technology), which eliminates incondensable gasses from the process.
The design of the plant took into account the world's highest quality standards and the most innovative environmental technologies. During the plant's regular operations and maintenance, all relevant safety and environmental standards are applied, as well as those to ensure respect for the local communities, in full compliance with the "sustainable plant" model: reusing materials, recycling waste, recovering and recirculating oils, monitoring the

storage of lubrication oils and using equipment to wash mechanical parts naturally and degrease them with organic methods.
The local territory can also count on important partners like the Consorzio Sviluppo Aree Geotermiche (Co.Svi.G.) and the Comunità del Cibo a Energie Rinnovabili, both crucial to promote the development of an agricultural production chain and food and wine culture that prioritizes sustainability. Local basil, tomatoes and flowers are cultivated in geothermal greenhouses. There are also food and wine itineraries that invite tourists to visit producers of cheeses, cured meats and beer, all made using geothermal heat.

Digitalisation

Furthermore, the plant has introduced digital checklists for each phase of its operations, solutions to limit energy consumption for lighting, and non-invasive barriers to protect local wildlife. The plant, moreover, is equipped with a sophisticated monitoring and remote diagnostic system, capable of ensuring the highest standards of reliability and efficiency.

Perspectives

Despite the increased costs of many equipment and services following the tremendous inflationary pressures on all segments of the supply chains as a result of the events over the past year, 2021 marked a return to growth for the geothermal heating and cooling industry, after several years of slow developments. New projects are constantly being announced and developments are progressing rapidly. The high energy bills now faced by households businesses across Europe are also triggering a switch to geothermal energy systems. The geothermal electricity market however, is now entering a transition phase, with only 35 MWe of new capacity addition across 6 plants.

Moreover, a new wave of innovative technologies brings new winds of hope for the geothermal electricity industry which has learned from the failure to scale up the EGS technology at the speed we hoped. Lithium is a particularly powerful buzzword, bringing the European Union and national governments to look closely at the potential of co-production of geothermal power, heating and lithium. The growing interest and potential for lithium for geothermal could increase investment in geothermal. Towards the end of 2021, plans for a rapid fuel switch in the heating and cooling sector emerged at the beginning of 2022 as Europe condemned Russia’s invasion of Ukraine.

Regarding reference assets, current defined assets will be updated with new data and new assets may be integrated. The report concludes that thanks to **continuous technological developments, geothermal resources that previously were out of reach will be explored and developed**. The new technological assets will make it technically and economically more feasible. These new assets like storage will be assessed in the upcoming years.

In the upcoming versions of the KPIs report, new aggregated data will be checked against real-life data.

Technical specifications

From the reference projects and assets, the learning curve will be assessed based on the real examples above, with well-understood cost structure in most common European tectonic settings. Furthermore:

- Possibly to consider a few rarer ones (e.g., hot spot/rifting/subduction zone volcanism/ intraorogenicsetting/ stable continental crust)
- Consider demand side that has most upside and is most relevant for Europe (NECP)
- ✓ Heating projects with a range of depth windows
- ✓ Combined heat and storage projects
- ✓ Combined heat and power projects

- ✓ Power projects
- Define state-of-the-art UTC (€/kWh) and subsets using open spreadsheets and publicly available data
- Hypothesize «if a reference project or reference asset were to be developed and if the developer applied outcomes from R&I projects funded in Europe, then the impact on UTCs (and subsets thereo) is …»
- Pick one DCF model that is open to the public, agree on reference projects and assets, then engage with Pis of research and innovation projects and allow them to comment on the final result using the discounted cash flow (DCF) model.

POTENTIAL COSTS REDUCTION

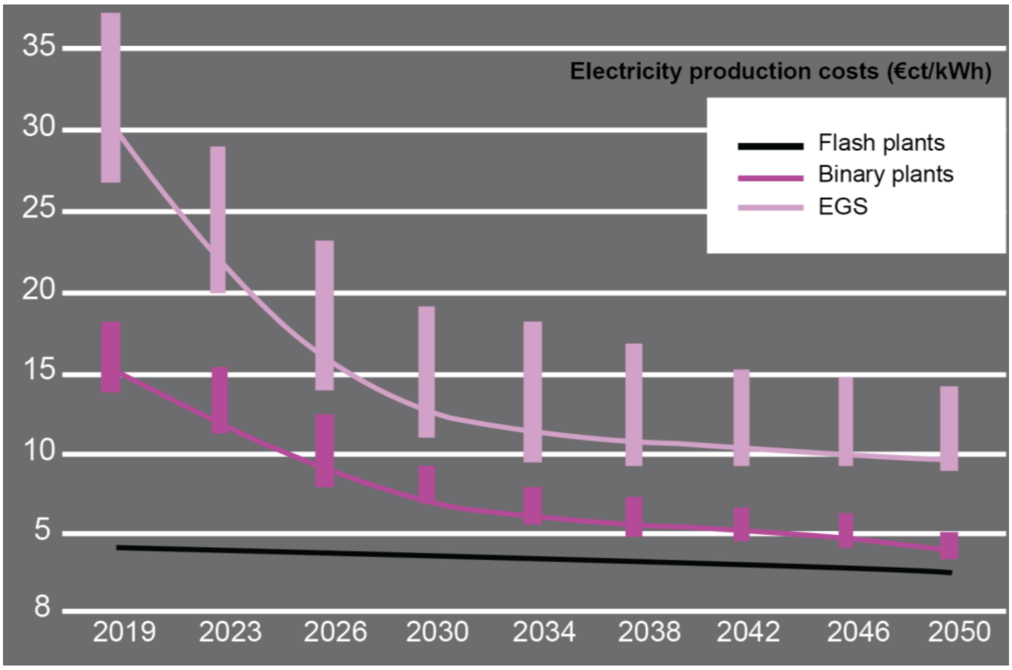


Figure 13: *Graphs on Potential costs reduction for geothermal electricity production (costs on €ct/KWh)*

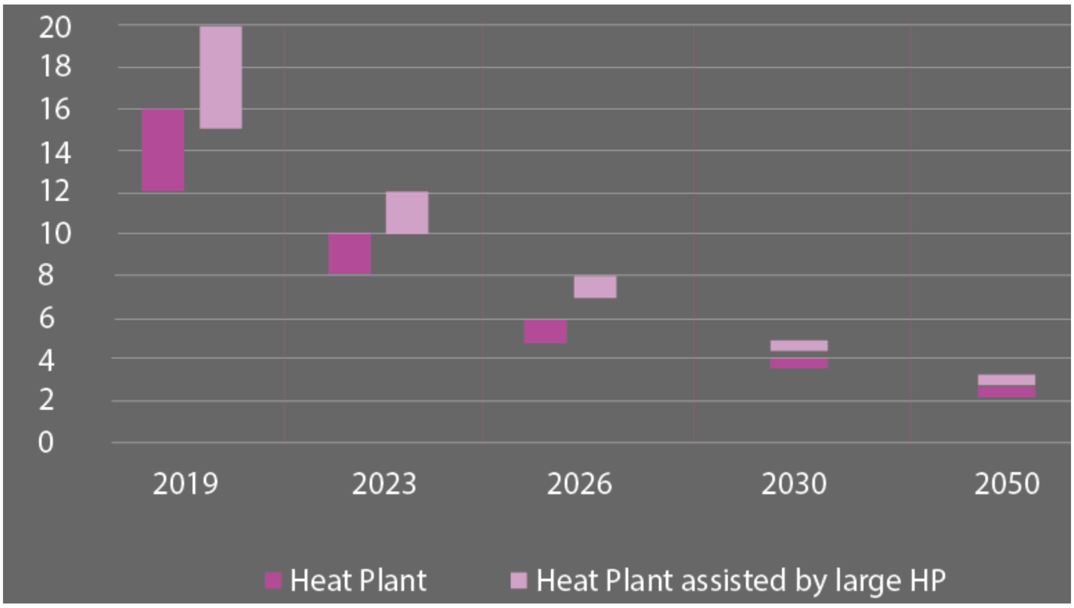


Figure 14: *Graphs on Potential costs reduction for geothermal heat production (costs on €ct/KWh)*