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Integrated Methodology for Distributed Geothermal Co-Heat and -Power Production and Its Application – A Case Study from the Pannonian Basin

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Abstract

Geothermal energy represents a reliable and low-carbon resource with significant potential for both heat and electricity generation, particularly in regions characterized by medium-temperature reservoirs such as the Pannonian Basin. However, the efficient utilization of these resources requires an integrated approach that simultaneously considers subsurface geological conditions and surface-level constraints. This study presents a comprehensive methodology for the first-order evaluation of geothermal resources for combined heat and power production. The approach integrates geological risk assessment, based on Common Risk Segment (CRS) and Composite Common Risk Segment (CCRS) mapping, with a GIS-based multi-criteria analysis of environmental, technical, and socio-economic factors. The methodology is applied to a case study in southwestern Hungary (Bóly region), where potential locations for new geothermal doublets are identified and evaluated. Preliminary reservoir simulations indicate that the selected doublets can provide up to 4.2 MW_{th} thermal capacity over several decades. The integration of geothermal heat into district heating systems, combined with electricity generation using Organic Rankine Cycle (ORC) technology, enables efficient cascading utilization of the resource. Under representative conditions, the system can supply a substantial share of local heat demand while producing several GWh of electricity annually. Another case study of an existing well near Szarvas (southeastern Hungary) was also presented. The results demonstrate that medium-temperature geothermal resources can support decentralized energy systems and contribute to improved energy security, resource efficiency, and decarbonization.

Keywords

geothermal energy, geothermal resource assessment, combined heat and power, energy system integration, ORC

1 Introduction

Geothermal energy is increasingly recognized as a reliable and low-carbon component of the future energy system. Unlike many other renewable energy sources, geothermal resources provide a stable, dispatchable energy supply with high capacity factors and lower, more predictable daily and seasonal variability. These characteristics make geothermal energy particularly valuable for both heat supply and electricity generation in decarbonized energy systems [1, 2].

Globally, geothermal energy has long been associated primarily with high-temperature volcanic regions and active plate boundaries; however, technological advances in drilling techniques, reservoir engineering, and power-conversion systems have significantly expanded the geographic range in which geothermal resources can be exploited. Recent analyses indicate that geothermal electricity could contribute substantially to future energy demand growth, with estimates suggesting that geothermal technologies could supply up to 15% of global electricity demand growth by 2050 [2, 3]. In Europe, advances in geothermal technologies are unlocking substantial technical potential beyond traditional geothermal hotspots. It has been estimated that around 43 GW of geothermal capacity could be deployed in the European Union at costs

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below 100 €/MWh, making geothermal electricity competitive with conventional fossil-fuel-based generation [3].

The Pannonian Basin is one of the most favorable geothermal regions in Europe, thanks to its relatively high geothermal gradient and favorable subsurface conditions (extensive presence of reservoirs) [4, 5]. The geothermal resources of Hungary can be characterized by two main play types: 1) the porous Neogen basin fill sediments, and 2) fractured–karstified Mesozoic carbonates, with temperatures between 50-100 ºC, and 90-120 ºC, respectively [6]. These resources are widely utilized for direct heat applications, including district heating, agricultural uses, and balneology [7]. Among these possibilities, various heating applications (where natural gas is replaced) and power production (due to the general applicability) are among the most desired. Also, one must keep in mind that, unlike other renewable sources, geothermal heat and power production are highly predictable and available year-round, with only minor daily and seasonal changes (in the case of power production), related to the ambient air temperature [8]. However, their potential for combined heat and power generation remains only partially exploited.

Electricity generation from low-temperature geothermal sources has become increasingly feasible due to the development of binary power plants, most commonly based on the Organic Rankine Cycle (ORC) [9]. In ORC systems, geothermal heat is transferred to an usually organic fluid with a lower boiling point than water, allowing efficient power generation even at relatively low temperatures [10–13]. Such technologies have enabled geothermal electricity production from resources previously considered unsuitable for power generation, significantly expanding the potential for geothermal deployment in regions dominated by medium- temperature reservoirs.

Beyond standalone electricity production, geothermal systems can also play an important role in integrated energy systems by simultaneously providing heat and electricity. Combined heat and power configurations enable cascading use of geothermal heat, where high-temperature resources are first used for electricity generation and the residual heat is subsequently used for heating purposes, thereby increasing overall efficiency. In regions with district heating demand, geothermal heat can serve as the primary energy source, while surplus heat can be used for electricity generation during periods of lower heating demand. Such integrated solutions improve the economic viability of geothermal developments while increasing resource utilization efficiency [1, 2].

Despite these technological advances, geothermal project development still involves significant uncertainties, particularly during the early exploration and site selection phase. Geological, environmental, and socio-economic factors must all be considered when identifying suitable locations for geothermal development. Integrating subsurface geological data with surface-level geographical and infrastructure constraints is therefore a key challenge in geothermal planning [14, 15].

The present study addresses this challenge by developing an integrated methodology for geothermal site selection that combines geological risk assessment with geographical and infrastructural considerations. Within this project, scenarios were investigated to extend existing geothermal operations towards both power generation and additional heat production. The proposed methodology integrates subsurface (geological) conditions with surface conditions and parameters to identify potential locations for new geothermal wells. The surface's geographical features define the key constraints for any construction, including those related to sub-surface operations, such as geothermal energy utilization in this case. These conditions can be categorized into three main groups: environmental, social, and technical. In addition to these constraints, surface characteristics also include the potential consumers, which can be described by their location, energy demand, and technical attributes. Therefore, the consideration of local geographical context is essential for medium and large-scale planning processes.

The methodology is applied to a case study in southwestern Hungary, where existing geothermal operations provide a basis for evaluating further development potential. By integrating subsurface geological information, surface geographical constraints, and potential energy demand, the study aims to identify promising locations for additional geothermal well doublets (production–injection pairs) and evaluate their long-term heat and power generation potential. Considering the heat demand of Bóly and its surrounding settlements, we further refined the site-selection procedure and provided predictions of long-term geothermal production. An additional site (Szarvas-Csabacsűd) was also analyzed to extend the scope of the study. The results demonstrate how medium-temperature geothermal resources can support decentralized energy systems by supplying both district heating and electricity generation through ORC technology.

2 Determination of geothermal potentials

The Bóly geothermal area is located in southwest Hungary, with a single operating (as of 2022) geothermal doublet of 2.5 MW_{th} installed capacity [16]. The geothermal production and injection wells are drilled east of Bóly, and have been in operation since 2002, providing heat supply for various public institutions. The geothermal wells target a fractured Jurassic limestone reservoir, with a flow rate of 17 l/s and production temperature of 76 °C from ~1.6 km depth [17].

The study area constitutes a 10 km radius circle around the centre of Bóly. The workflow started with the geological investigation of the area based on various available datasets. We collected information about the currently operating well doublet system from the Geothermal Information Platform [16]. Lithologies from all available boreholes of the study area as well as seismic sections, were collected from the database of the Geological, Geophysical and Mining Data Store [18]. Additionally, structural geological maps of [19] and [20] were utilized to constrain the geometry of the geothermal reservoir (fractured Jurassic limestone) in the study area. Based on this information, we produced maps of the depth, thickness, and temperature of the geothermal reservoir. It is important to note that the available geological and geophysical datasets for the region are limited and were only suitable for the first-order mapping of geothermal potential. The final selection of well locations should rely on additional local geophysical exploration and evaluation.

The reservoir geometry and temperature maps served as input for evaluating geological risks associated with geothermal development. We applied a relatively simplistic method to assess the uncertainty of driving subsurface parameters including (1) temperature, (2) hydrogeology (~permeability and presence of geothermal fluids), (3) geochemistry (~fluid composition), by creating Common Risk Segment (CRS) maps (e.g. [14, 15]) for these three main components. These three risk factors are generally considered the most relevant for geothermal project success/failure (e.g. [17] and references therein). Previous attempts for geothermal risk assessment in Hungary [21, 22] used multiple parameter combinations and scale-dependent workflows, providing the more complete representation of subsurface uncertainties. The advantage of our simplistic approach is that the independence of driving parameters is ensured in the probabilistic framework, providing a straightforward interpretation and enabling integration with surface factors. The CRS maps quantify the geological probability (Chance of Success – CoS) of a geothermal project in terms of the different factors. Therefore, a target temperature, flow rate, and chemical composition must be defined to produce the maps. We chose the parameters of the operating geothermal doublet (production temperature of 76 °C, flow rate of 17 l/s and relatively low gas content) as target values. The resulting CRS maps are presented in Fig. 1, indicating higher CoS in an E-W oriented band, constrained by two so-called fault structures in the north and southwest outlined in Fig. 1(a). Along these faults, the reservoir is basically "cut" and elevated to a near-surface position in the northern and southern part of the study area, resulting in very low predicted reservoir temperatures that are not sufficient for utilization (Fig. 1(a), red colour).

Based on the three component CRS maps, we produced a Composite Common Risk Segment (CCRS) map representing the overall geological CoS for geothermal reservoir development (Fig. 2). The CCRS map is created by

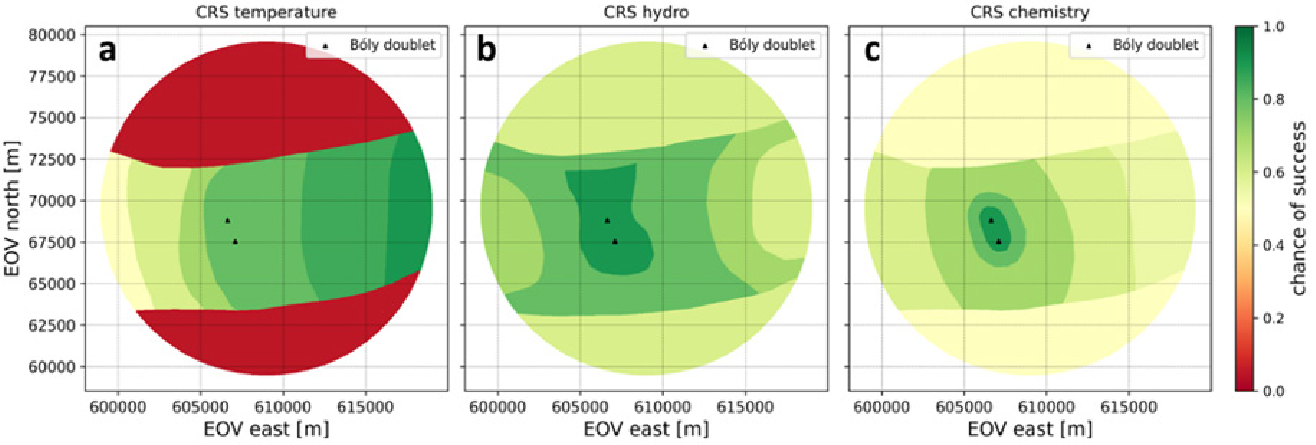

Fig. 1 Common risk segment (CRS) maps for the three main geological risk components of geothermal development (a) temperature, (b) hydrogeology, (c) geochemistry

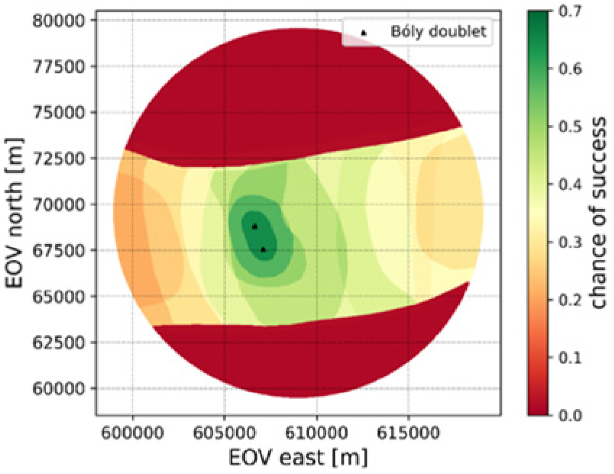

Fig. 2 Composite Common Risk Segment (CCRS) map representing the integrated geological risks. Greenish values show a higher chance of success, indicating suitable areas for geothermal development.

multiplying the three components. The CCRS map indicates the highest CoS in the vicinity of the operating geothermal doublet. This results in having information from this location, while further away, the factor of increased uncertainty is mirrored in the decreasing values. Still, the greenish to light yellow areas could be considered for potential development. The CCRS map was further integrated with various surface factors to narrow the areas that can be considered for development.

Data collection regarding the geographical factors was done using official EU and Hungarian databases (National Regional Development and Spatial Planning Information System, Corine Land Cover) for spatial and technical attributes, completed by open-source data (OpenStreetMap (OSM) and satellite images from Google). The road network of the OSM was extended by manual satellite image interpretation, considering dirty roads and other lower-level roads. Since official data regarding the annual heat demand of the Hungarian settlements does not exist, the pan-European HotMaps database was used [23]. Each settlement was associated with the values of the heat demand raster covered by their extent. The spatial data were processed and implemented into a GIS (Geoinformatics System) environment using ArcMap 10.4 software [24]. Population, the number of households and energy consumption data were collected from the Hungarian Central Statistical Office for each settlement included in the study area.

Each geographical feature was considered as a site suitability factor for finding the most favourable locations of geothermal wells. The criteria were categorized by their properties and were associated with value scores. The process was done empirically except for the Chance of Success layer. For most of the criteria, exclusion categories were considered as areas forbidden for construction of any geothermal facility, including the 800 m impact zone of the operating geothermal wells to the west of Bóly (Fig. 3). Each vector layer was converted to a raster to fill the raster cells by their value scores. If any of the cells received 0 value score on a criterion layer, the location of that cell was considered as prohibited area regardless of its values by other suitability criteria. The suitability value scores were weighted according to their importance during the final suitability evaluation. The extreme importance of the geological conditions was highlighted by multiplying its values by 0.5, while land use, nature reserve and residential areas received a 0.1 weight. The power grid accessibility criterion was multiplied by 0.05 and road network proximity by 0.15. Considering the criteria and their weightings, the final site suitability map was created (Fig. 3). Environmental, geological, and social aspects were integrated in this way into a single layer.

Based on this integrated site suitability map, we highlighted potential subsurface (i.e. reservoir level) and surface positions of well doublets (Fig. 3). We concentrated on locating a maximum number of potential geothermal doublets in the study area, similar to the methodology described in [25]. For the positioning of the wells, we considered the orientation and relative magnitude of the present-day stress field in the area and the geometry of pre-existing geological structures in the reservoir. These factors are essential to minimize drilling risks and maximize well productivity, while further on-site geophysical measurements would be necessary to verify the suggested orientations.

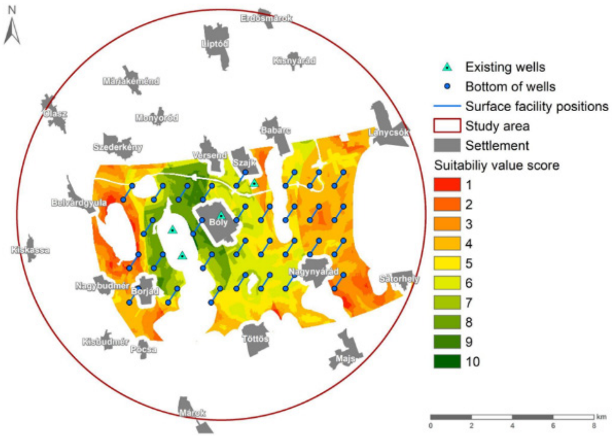

Fig. 3 Geothermal facility site suitability of the rated area and the well doublet location alternatives. Void areas are prohibited for geothermal development. Straight lines between the well bottom points represent the possible location of the surface geothermal facility.

The total rated area (value score > 0) is 74.4 km^2, 23.7% of the total study area. Areas characterized by value scores 6-10 were identified as potential sites for geothermal well drilling and its surface facility. Their extent is 13,3 km^2, only 4.2% of the total study area. Location alternatives for the well doublets are also presented in Fig. 2. Two doublets were selected, one of each side of the highway which crosses the study area. The highway was considered as a barrier for geothermal district heating pipelines. The pipeline layouts from the geothermal surface facilities to the consumers, i.e. the point features representing the centroid of the settlements, were designed based on the local road network by using the Network Analyst tool in ArcMap. The main criterion is to find the shortest route from the heat source to the demand points, regardless of their distance. The local highways were identified as barriers that pipelines could not cross. Distances on the road network from the heat sources are presented as a heatmap, along with the suggested district heating pipeline layouts in Fig. 4. Out of the 19 settlements, 9 are connected to the southern facility (near Bóly), and 10 can be connected to the northern one (near Szajk). The mean pipeline length is 8,405 m, while the longest route is 12,450 m, connecting Kiskassa to the southern facility.

With the help of a 2D numerical simulator [26], we modelled the performance of the two selected doublets near Bóly and Szajk (Figs. 4 and 5(a)) for a period of 200 years. For the modelling, we chose a constant reinjection temperature of 35 °C for simplicity and a constant flow rate of 20 l/s (Fig. 5(b)), while, as mentioned before, further local exploration should be conducted to refine these assumptions and provide more precise estimates on doublet performance. Temperatures in the reservoir start to drop near the injection wells as the cold water propagates through the fractures/pores of the reservoir rock (Fig. 5(a)). The theoretical capacity of both doublets is around 4.2 MW$_{th}$ for ~75 years (Fig. 5(c)), followed by a significant drop due to the decrease of production temperature associated with the cooling of the reservoir due to reinjection (the cold water front emerges towards the production wells). It is important to keep in mind that production temperatures and doublet capacity may drop earlier in case of higher

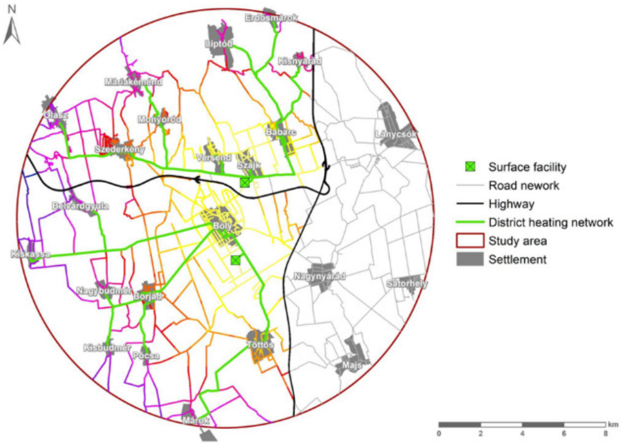

Fig. 4 Suggested district heating pipeline network layout connecting the new geothermal facilities with the consumers

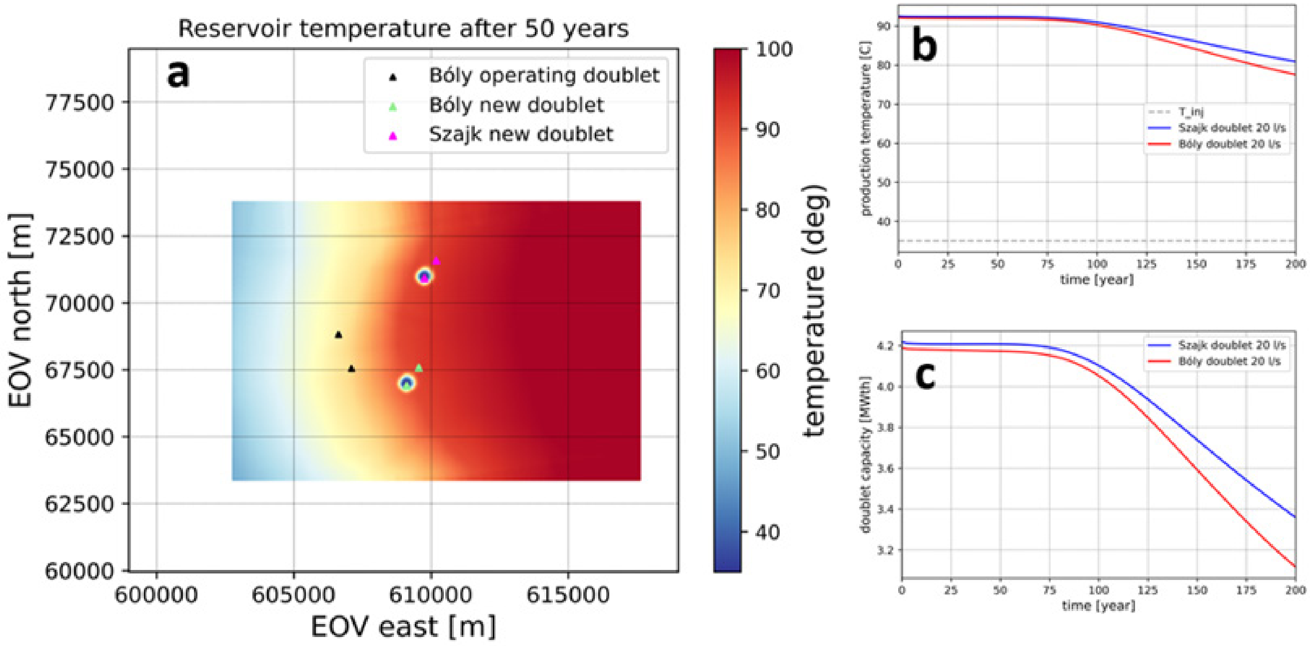

Fig. 5 (a) Modelled temperature in the reservoir after 50 years of geothermal operation of the Szajk and Bóly new doublets. (b) Evolution of production and injection temperatures, and (c) theoretic doublet capacity for the period of 200 years.

flow rates or different reservoir properties (e.g. higher permeability). Additionally, in the case of electricity generation, the capacity of the system depends on the efficiency of the binary power plant, determined by, e.g., the type of working fluid and production temperatures.

3 Utilization of geothermal heat for heating and power production

The temporal distribution of the heating demand is determined by the outdoor temperature, for which data are taken from a TMY (Typical Meteorological Year) database [27] describing an average year in hourly increments. The annual heating demand was divided into hourly heat demands in proportion to the difference between the assumed indoor temperature of 20 °C and the ambient temperature at the current hour. The nominal supply and return temperature of the heating system was assumed to be 70/50 °C, but this temperature is required only at the nominal outdoor temperature of −11 °C for Bóly. As the heat transfer surface of the heaters is constant, the heaters can transfer the required heat to the air of the room at lower temperatures if the heat demand is lower than the nominal one. The heating water temperature affects the return temperature of the geothermal fluid, thus the heat output that can be extracted from it. At high ambient temperatures, the geothermal heat can supply the entire demand, whereas, below a certain temperature, an additional peak heat source is required, as shown in Fig. 6.

For geothermal fluid temperatures below 100 °C, power generation can be achieved using an Organic Rankine Cycle (ORC). The efficiency of power generation depends on the temperatures of the heat input and heat removal, as well as on the cycle design and working fluid. Since the latter is not known at the preliminary design stage, the efficiency of the ORC cycle was assumed to be 40% of that of the Carnot cycle at the same temperature limits, based on empirical examples. The vaporization temperature was 10 °C lower than the well-head temperature, and the condensation temperature, assuming air condensers, was 15 °C higher than the ambient temperature. The model thus constructed takes into account the seasonal variation of efficiency, and hence of electrical output, through the ambient temperature.

For the on-surface installation, a combined system was assumed to be used for heating and power generation, with a priority on satisfying heating demands first, with the remaining mass flow going to the ORC system. In this way, both the geothermal share in the heat supply can be maximized, and the summer use of geothermal heat can be solved. The drawbacks are the relatively high investment cost and lower utilization of the ORC system compared to a fully power-producing geothermal power plant, which increases power production costs. In such a case, however, the economics can only be understood for the two systems together, and the revenue from the heat supply may offset the higher costs.

For district heating, the key question is how much of the annual connected demand can be met by geothermal heat; for power generation, the key issue is the amount produced annually. The parameters that determine these quantities are the well-head temperature, the fluid mass flow rate, and the annual heat demand of the consumers connected to the geothermal district heating system. The well-head temperature of the selected well pair near Bóly – for this application – is taken as 91 °C, and the heat demand is considered to be 75% heating and 25% for Domestic Hot Water (DHW). The vertical axis in Fig. 7 shows how much of Bóly's 25.63 GWh annual heating heat demand can be connected to the newly developed geothermal district heating system, while the horizontal axis shows the fluid mass flow. If we could connect consumers that account for half of the total heat demand to the district heating system, we would need a mass flow of about 35 kg/s to cover the entire heat demand. In this case, the system would be able to produce

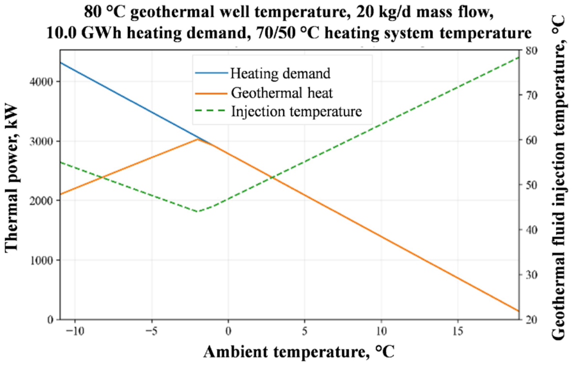

Fig. 6 Heating demand and geothermal fluid reinjection temperature as a function of ambient temperature in a given outlet temperature

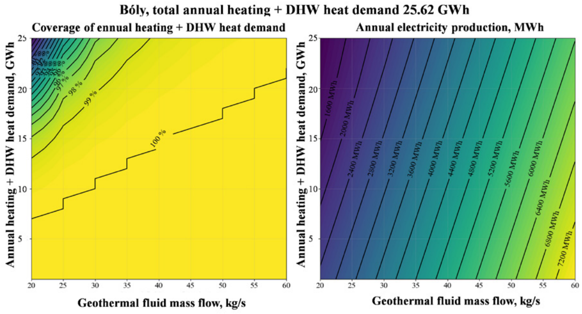

Fig. 7 Percentage of heat demand and the amount of additional power that can be produced as a function of the geothermal well mass flow and the annual heat demand

about 3600 MWh of electricity per year, with an average of 400-420 kW power. This power might be sufficient for various purposes; it can even serve as the energy source for a 7/24 on-site hydrogen refueling station [28, 29], providing a good example of the multi-purpose use of a heat source.

One of the uses of these power&heat systems is the possibility of constructing a power-grid-independent local heating system, where the ORC device can generate power sufficient to support all systems needed to keep the heating operational during local or general power failure, even when the power grid is totally collapsing. When the net power is sufficiently high, even part of the local critical infrastructure can be powered by this local, day-and-night source.

4 Utilization of the geothermal heat of an existing well

If geothermal heat cannot be fully utilized locally due to insufficient local heat demand, it can be partially converted into electricity using an ORC [30]. The design, efficiency, and performance of such systems depend on the key input parameters, including geothermal fluid mass flow, wellhead temperature, and ambient conditions (particularly in the case of an air-cooled condenser). The selection of working fluid and expander type for these input parameters plays a crucial role in optimizing power output and thermal efficiency [31]. To support the deployment of multiple small-scale geothermal units, a uniform methodology has been developed to rapidly determine the optimal working fluid and estimate performance. The simulations were carried out using Asimptote's FluidProp [32] and Cycle-Tempo [33]. A schematic diagram of an ORC is shown in Fig. 8. In our calculations, we use a thermal water yield of 40 l/s.

There are several locations in Hungary and, more broadly, in the Pannonian Basin where existing geothermal wells could simultaneously supply heat and electricity, depending on local demand and market conditions. Despite this potential, only a limited number of installations currently utilize geothermal resources for electricity generation, typically through small or micro-scale ORC units [34].

A detailed case study was conducted for the Szarvas K-110 geothermal well, located near the village of Csabacsűd, where a potential injection well (Csabacsűd B-50) is also available. The proximity of Szarvas, a medium-sized town with an existing district heating network, further enhances the feasibility of integrated utilization.

The current heat demand of the Szarvas district heating system is approximately 500 GJ/year, with plans for future expansion; therefore, additional heat sources would be easily utilized.

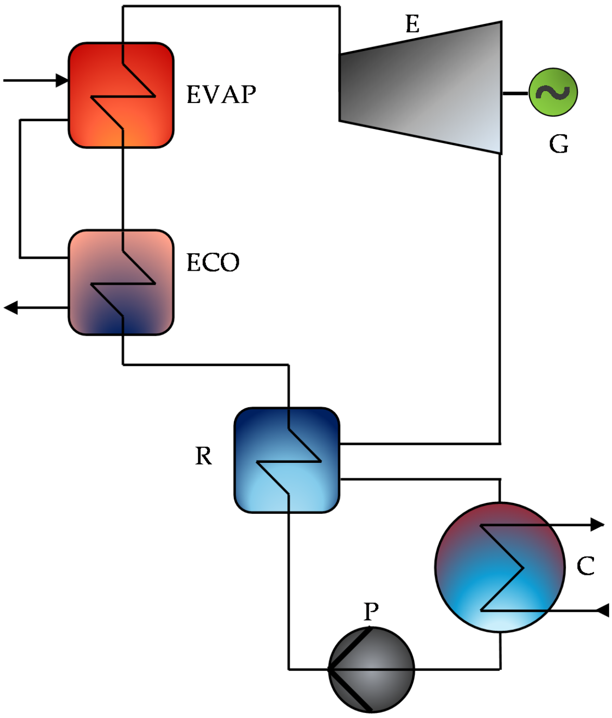

Fig. 8 Layout of an ORC system, utilizing geothermal heat source as a heat source

The Szarvas K-110 geothermal well, with a current production temperature of 98 °C and a potential increase to 120-125 °C through deeper drilling, and a maximum flow rate of up to 80-93 l/s, might be sufficient to meet the heating demand, and the remaining heat could be further utilized [16].

This thermal energy can be used to generate electricity with an ORC unit. Although these temperatures are relatively low compared to conventional power plants, ORC technology enables efficient power production even below 100 °C, provided that appropriate working fluid-expander combinations are selected [35]. A practical example is the Tura geothermal power plant in Hungary, which operates with approximately 120 °C thermal water and has an installed capacity of 3.35 MW_e [36, 37].

Due to their compact and modular design, such ORC units can be transported and integrated into existing geothermal systems within a short installation time. These systems are typically air-cooled, which simplifies deployment but makes performance dependent on ambient conditions.

Based on the current study, the geothermal system is capable of supplying both district heating and electricity. The expected performance indicates approximately 700 kW of thermal output and 540 kW_e of electrical power under realistic operating conditions. The ORC design is shown in Fig. 8, where R denotes the recuperative heat exchanger, ECO the liquid heater (economizer), EVAP the evaporator, E the expander, G the generator, C the condenser, and P the pump. The self-consumption of the geothermal co-heat and power system is negligible on the thermal side but more significant on the electricity side, resulting in an estimated annual net electricity production of approximately 4730 $\mathrm{MWh_e}$.

From an economic perspective, electricity prices were evaluated using Day-Ahead Market data provided by AFRY [38], with 2023 selected as a representative year that captures the decade well. Although the total power output is relatively modest, the use of existing geothermal infrastructure significantly reduces investment costs. As a result, the estimated return on investment (ROI) is below 7 years, indicating strong economic viability.

With deeper drilling and enhanced parameters, 10.49 $\mathrm{MW_{th}}$ thermal energy can be utilized from the heat source. With the ORC design shown in Fig. 8 and butane as the working fluid, 1.18 $\mathrm{MW_e}$ of power is achievable after satisfying the district heating network's heating demand, although increased drilling costs might exceed the gains on the power production side.

5 Conclusions

In this study, an integrated methodology was developed to identify and evaluate geothermal resources for combined heat and power production. The proposed approach systematically combines subsurface geological assessment with surface-level geographical, environmental, and infrastructural constraints, enabling a more comprehensive and realistic site-selection process for geothermal developments.

On the subsurface side, CRS maps were generated for temperature, hydrogeological, and geochemical factors and integrated into a CCRS map to quantify the overall geological chance of success. This probabilistic framework enables spatial characterization of geothermal potential while explicitly accounting for uncertainty. On the surface side, geographical constraints and demand-side factors were incorporated through a weighted multi-criteria GIS-based evaluation, resulting in a unified site suitability map. The combination of these approaches represents a key contribution of the present work, enabling the simultaneous consideration of resource availability and utilization conditions.

The methodology was applied to a case study in the Bóly region, where two potential geothermal doublets were identified. Long-term reservoir simulations indicate that these systems can provide up to 4.2 $\mathrm{MW_{th}}$ thermal capacity for several decades (~75 years), demonstrating the feasibility of sustainable heat extraction under the assumed operating conditions, while these predictions should be further refined based on a local exploration campaign. The integration of these systems into a district heating network showed that a significant portion of local heat demand can be supplied by geothermal energy, while surplus thermal energy can be converted into electricity using ORC technology. Under representative conditions, the combined system could produce on the order of several GWh of electricity annually, highlighting the potential of medium-temperature geothermal resources for co-generation applications.

The results also demonstrate that distributed, small-scale geothermal systems can contribute to the development of decentralized energy infrastructures. Such systems are particularly advantageous in regions with dispersed heat demand, where centralized large-scale solutions are less feasible. In addition to providing baseload heat supply, geothermal-based combined heat and power systems can enhance local energy security and resilience, for example, by enabling partial operation of district heating systems during power grid disruptions.

The extended analysis carried out for the Szarvas–Csabacsűd area further confirms that existing geothermal wells can be effectively retrofitted for combined heat and power production. The results indicate that such systems can simultaneously meet local heating demand and generate electricity, with favorable economic performance, particularly when existing infrastructure is used. This highlights the importance of re-evaluating already available geothermal assets in the context of integrated energy system development.

Despite these promising results, several limitations of the study should be noted. The geological assessment is based on available datasets, which may be sparse or uncertain in certain areas, and therefore, the predicted reservoir properties should be validated by detailed site-specific geological and geophysical investigations prior to drilling.

Overall, the presented results demonstrate that medium-temperature geothermal resources, when evaluated using an integrated subsurface–surface methodology, can play a significant role in the transition towards low-carbon, decentralized energy systems. By enabling both heat supply and electricity generation, such systems can help reduce fossil fuel dependence, improve energy system flexibility, and support long-term sustainability goals.

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