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Case Study of Using the Geothermal Potential of Mine Water for Central District Heating—The Rožná Deposit, Czech Republic

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Abstract: This paper analyzes the possibility of using the thermal energy of discharged environmentally friendly mine water for the heat supply of a selected locality. There are few cases of industrial use of geothermal water in the Czech Republic, but mine water has never been the source. Based on this fact, an analysis of the usability of mine water at the Rožná I Mine was carried out. The analysis showed that the energy output of this pumped water was sufficient for the selected location of the municipality of Dolní Rožínka, where long-term annual average consumptions are at a level of 4350 GJ. The theoretical maximum output of this source is calculated as 837.4 kW; therefore, it exceeds the output required to satisfy the energy needs of this location several times over. Based on this input information, a technical and economic model of the heating system installation project was developed with three options. The case study aimed to find and propose an optimal alternative solution to replace the current unsatisfactory state of heat supply in the village of Dolní Rožínka. In the final part of this paper, the most optimal option is identified by a comparative method, which replaces the existing central district heating based on the production of heat energy from natural gas, i.e., fossil fuels. This study was motivated by a strategy to replace fossil energy sources with renewable energy sources wherever conditions are suitable.

Keywords: waste mine water; close mine; geothermal energy; mine renewable energy; renewable district heating; Rožná

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Citation: Vokurka, M.; Kunz, A. Case Study of Using the Geothermal Potential of Mine Water for Central District Heating—The Rožná Deposit, Czech Republic. *Sustainability* **2022**, *14*, 2016. https://doi.org/10.3390/su14042016

Academic Editors: Désiré Rasolomampionona and Klos Mariusz

Received: 11 January 2022
Accepted: 8 February 2022
Published: 10 February 2022

1. Introduction

Reducing the use of traditional fossil fuels for electricity and heat generation is a current global trend, as the world seeks to obtain energy from other, more environmentally friendly sources. The European Green Deal [1] states that the switch to alternative sources is the starting point for pollution-free energy production [2]. Following this decision, low-potential geothermal energy becomes an interesting alternative to the current heating system, whether in industrial or non-industrial use in Czech legislation. Non-industrial use, i.e., installation of heat pumps in houses or non-commercial use in other premises, is supported by the state and the European Union by investment and operation funds. The number of installations using low-potential geothermal energy in the Czech Republic has long been around 1400 per year [3]. Technically and economically available high-potential geothermal energy for electricity and heat production in the Czech Republic is practically absent. As already mentioned, more than a thousand projects of various sizes are installed annually based on pumping low-potential geothermal energy as a source for heating and hot water. As far as the authors are aware, there is only one project in the Czech Republic that uses groundwater heat as one of the energy sources for central district heating (CDH), and that is in the city of Děčín in the north of the Czech Republic [4].

There are numerous mine water discharges in the Czech Republic [5,6], where warm mine water is discharged into local watercourses without further use. For this reason, abandoned or ending deep mines may be a suitable source of geothermal water, the exploitation of which may be one of the best options to utilize the potential of closed deep mines [7,8]. The temperature of groundwater increases with the depth of formation. Groundwater has a constant temperature with little dependence on the season. The average temperature in Central Europe at a depth of 10 m below the surface is about 9.5 °C [9,10]. However, the temperature is not routinely measured [11]. Moreover, the usable geothermal potential of the mine water of individual sites is influenced by the concept of its management, i.e., the method of pumping, treatment and discharge.

Among the first applications of this kind, i.e., industrial use of mine water, is the use of 18 °C mine water from the flooded Springhill Mine in Nova Scotia (Canada), which started in 1992. The application of this process was implemented with 11 heat pumps with a total capacity of 41 kW, which heated 16,700 m^2 worth of buildings [12,13]. In the Netherlands, on the other hand, boreholes pumped mine water from flooded coal mines up to 28–30 °C to provide primary energy to heat pumps with a total capacity of 700 kW. After an upgrade in 2013, this central district heating network covers an area of up to 115,000 m^2 [14,15]. Another industrial application is on the German side of the Erzgebirge at the Marienberg ore deposit. Since 2006, mine water at a temperature of 12 °C has been pumped at this site, and the heating system has a total capacity of 690 kW. A central district heating is used in commercial buildings in the nearby town [16].

Mine water utilization is analyzed and re-evaluated in many European countries nowadays. As an example, several projects can be mentioned in the UK. In 2020, Lanchester Wines, a private company based North East England, has installed 2.4 MW and 1.6 MW mine water-based heating systems, currently the largest in the UK, to heat two warehouses in Gateshead. This development is expected to be followed by an even larger scheme, 6 MW, led by Gateshead Council, which will use mine water as the heat source for a planned expansion of the local central heat district system. Another scheme, 3.5 MW (with potential for more), also in North East England, is planned as part of the new Seaham Garden Village development. Analysis of heat production from underground mine water in broader socio-economic and environmental aspects in UK has been prepared and presented in [17].

The issue of using the energy potential of groundwater from closed mines is currently also the subject of research and development tasks. An example is the international project called Vodamin II, which took place with the financial support of the Cross-Border Cooperation Program between the Czech Republic and the Free State of Saxony in 2014–2020. The project solution also included an evaluation of the theoretical energy potential of water in the flooded quarries of the North Bohemian Brown Coal Basin [18].

At least two similar installations are in the Czech Republic. One of them is the use of mine water from the Ostrava-Karviná coalfield, which has a temperature of 26–29 °C to heat the Jeremenko shaft area [19,20]. The second one may be the use of uranium mine water with a temperature of 21–22 °C to heat a mine water treatment plant after uranium mining in Příbram [21]. A single industrial application was considered at the Olší-Drahonín deposit in 2007, when uranium mine water at a temperature of 10–12 °C was to be pumped in a closed system and used for the central district heating in the Drahonín municipality [20,22,23]. However, this project was never implemented. The ending mining activity at the Rožná deposit, which is close to the Olší-Drahonín deposit, offers a project of a similar nature. However, the Rožná deposit has some additional advantages. These include the temperature of the mine water, which, after decontamination, reaches up to 16 °C, assuming that the cost of pumping it from underground will be minimal. An equally important advantage is the existence and possible use of the existing central district heating boiler plant, including the distribution network in the village. The current state of the energy equipment of the central district heating system in Dolní Rožínka is morally and technically obsolete, requires major upgrading and can also be considered an advantage.

The submitted manuscript factually explains the favorable conditions of the selected site and presents the research results for the possible implementation of the project. The key contributions of the study can be presented as follows:

- The research identifies and defines the most suitable location from a set of sites in the Czech Republic that are suitable for thermal energy production;
- The research presents a proposal for three possible technical solutions with partial use of the existing central district heating infrastructure;
- The research presents an economic model of each technical solution, on the basis of which it is possible to proceed to the eventual implementation of one of them.

2. Case Study Description

The source of geothermal potential for this case study is mine water from the Rožná deposit, which is decontaminated and then discharged into the local watercourse in a controlled manner. The Rožná I Uranium Mine, which is part of the Rožná deposit, is located in the central part of the Czech Republic on the edge of the Bohemian-Moravian Uplands, approximately 60 km northwest of Brno (see Figure 1). The GEAM Dolní Rožínka spin-off plant, which is part of the state enterprise DIAMO in Stráž pod Ralskem, carries out permitted mining activities in the 8.762 km^2 mining license [24]. The main activity between 1957 and 2017 was the underground mining of uranium ore and its subsequent processing into uranium concentrate. Currently, partial flooding of the mine is underway, which will be stopped below the 12th level. The unflooded mine areas will continue to be maintained and used for exploration purposes over a planned 10 to 15-year period.

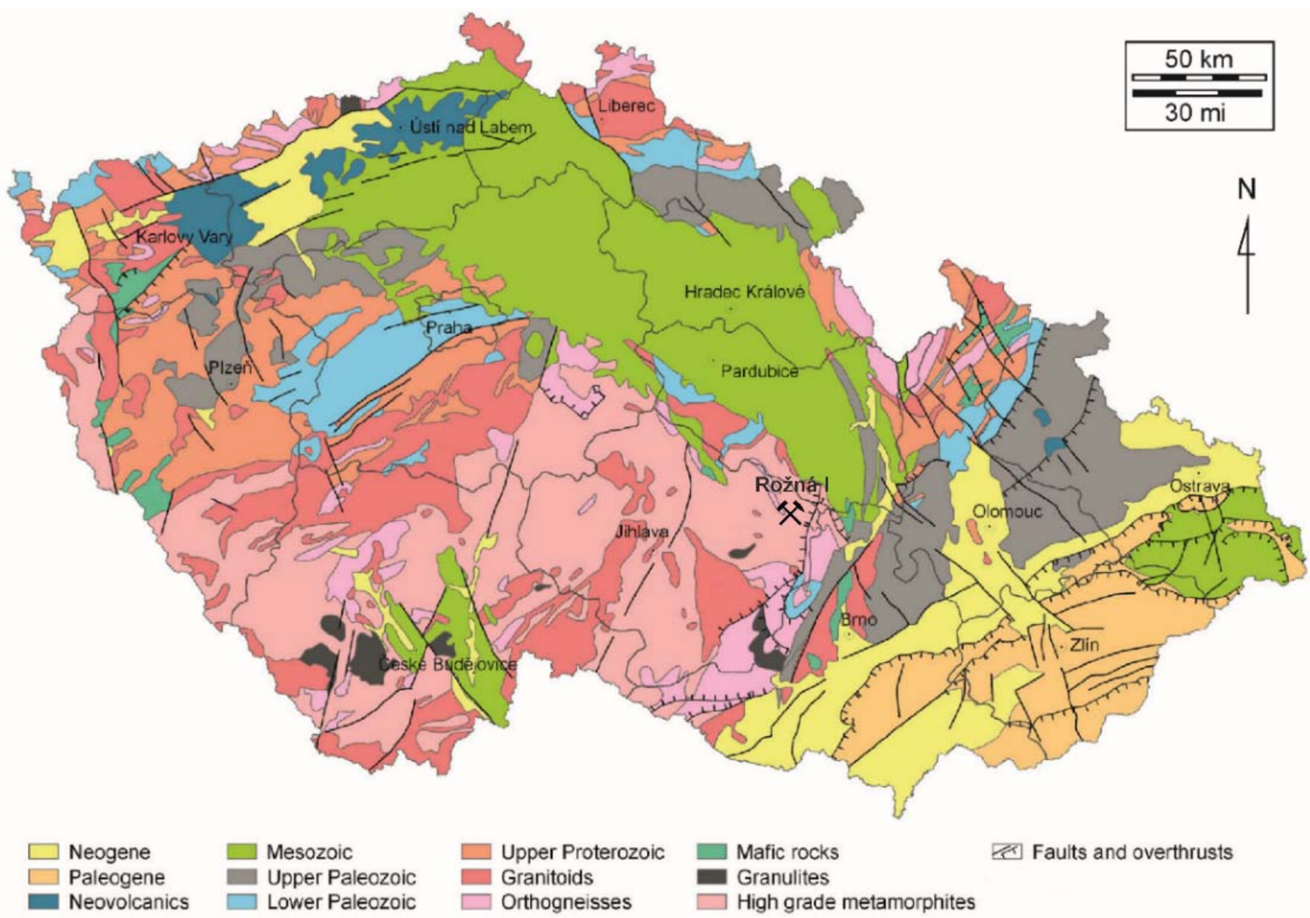

Figure 1. Simplified geological map of the Czech Republic showing the Rožná I Mine [25].

The Rožná I Mine pumps mine water through the R1 shaft and B1 shaft. As already mentioned, a part of the deposit is currently flooded. Therefore, the assumed maximum flow rate of 48 L.s^{-1} of pumped water can only be expected after 2024, when mine water reaches the level of the 12th level and when pumping is resumed in full [26]. The use of this volume is conditional on the construction of two supply pipelines to the two decontamination stations R1 and Bukov. The decontamination stations are pumped with mine water at a temperature of 10–12 °C, with treated water at 16 °C at their outlets. It is therefore appropriate to locate the equipment for the abstraction of these waters for the CDH purposes of the municipality of Dolní Rožínka. As this is decontaminated mine water, it is possible to consider its controlled discharge into the watercourse after previous use.

The buildings in the northern part of Dolní Rožínka, located within 3 km of the geothermal water source, are considered as consumption points for the thermal energy produced in the case study. Due to the ever-increasing price of heat, the unsatisfactory operation of the central gas boiler plant, and possible investment support, there is interest in Dolní Rožínka in relation to this alternative source of heat energy. The current state of the gas boiler plant corresponds to its age. The equipment was installed in 1991 and now requires significant reconstruction. According to the statistics of heat consumption of end users in the municipality of Dolní Rožínka, it is possible to calculate an average heat consumption of around 4350 GJ per year. Average monthly heat consumption depends on the season, while the instantaneous (hourly) maxima and minima depend on the instantaneous outdoor temperature. In the current boiler plant, it is impossible to control production flexibly according to actual consumption, which is resulting in significant energy and financial losses, especially in the summer months. In the current operation of the boiler plant in Dolní Rožínka, these losses amount to around 30% of the total average production over the last three years, i.e., 6000 GJ of heat (see Table 1) [27–29]. The gradual increase in losses year by year is caused mainly by due to the shutdown of the 140 kW cogeneration unit. This unit was put out of operation in April 2019 due to its poor technical condition, and the efficiency of the boiler plant has deteriorated.

Table 1. Balance statistics of heat production and sales from the boiler plant in the municipality of Dolní Rožínka [28,29].

Year	Production	Sales		Losses	
	GJ	GJ	%	GJ	%
2020	6033	4052	67.1	1982	32.9
2019	6320	4380	69.3	1940	30.7
2018	5925	4336	73.2	1590	26.8

3. Results and Discussion

In the initial phase of project preparation, it was necessary to analyze the total available energy potential of mine water for practical use in the case study area. Based on the available data, a technical model for implementation was defined with three options. For each technical option, a simple financial model was developed to compare the different technical solutions from an economic point of view. Due to the simplicity of the model and the variability of the input data, i.e., prices, it is not possible to evaluate the presented models in absolute terms. The purpose of this study is to show, while still holding the economic inputs constant, the most appropriate technical and economical option.

3.1. Analysis of the Available Geothermal Potential of the Rožná Deposit Mine Water

For the purpose of analysing the use of mine water for the CDH, extensive research on the geothermal potential of mine water from the Rožná deposit was carried out [30]. The Rožná deposit is part of the Stráž Moldanubian, where rocks of varied and monotonous groups of metamorphites and igneous rocks are exposed (see Figure 1). The monotonous group is mainly composed of different types of paragneiss. The varied group is composed of paragneiss with a number of intrusive rocks such as graphitic rocks, amphibolites, calcium-silicate hornblendes, crystalline limestones, ultrabasics and granulites. In addition to metamorphosed rocks, there are also numerous granitoid massifs and veins of aplites and pegmatites throughout the area [31]. The Moldanubian has a rifted structure that was formed as a result of Variscan orogeny. During the emplacement of the Moldanubian thrust plates, an isoclinal fold structure was formed in the NE-SW direction, which is very strongly faulted under conditions at the interface of ductile and brittle deformation.

This geological structure of the deposit subsequently defines the thermal conductivity coefficient of the rocks [32–34]. The rock mass of the Rožná deposit exhibits a pronounced rock anisotropy, which is significantly reflected in the thermal conductivity of the rocks, e.g., the thermal conductivity of fine-grained paragneiss is considerably higher than that of gabbro-diorites [35]. The average thermal conductivity depends on the type of rock. In the Rožná deposit, it ranges from 1.5 to 2.7 $W.m^{-1}.K^{-1}$, and exceptionally up to 3.2 $W.m^{-1}.K^{-1}$ [36]. Other main parameters characterizing the temperature rise in the Earth's crust include the so-called geothermal degree or its inverse value, i.e., the geothermal gradient. The geothermal degree at the Rožná deposit was determined as having an average value of 55.86 $m.^{\circ}C^{-1}$, and the geothermal gradient was determined to be 0.0179 $^{\circ}C.m^{-1}$ [30]. The value of heat flux, which is closely related to the tectonic structure, cannot be neglected either. This value ranges from 30 to 120 $mW.m^{-2}$ on the continents, with an average temperature of about 60 $\pm$ 10 $mW.m^{-2}$ [37]. Lower heat flux is observed on the old continental shields. It is for this reason that a below-average value of 27–48 mW^{-2}. was measured in the area of interest [38]. Another significant source of terrestrial heat is the spontaneous decay of radioactive elements (isotopes of U^{235}, U^{238}, Th^{232}, K^{40}) in scattered rocks. A correlation between the total gamma activity and heat production of rocks has already been demonstrated. Syenites, granodiorites and igneous rocks show high heat production (5.9–2.7 $\mu W.m^{-3}$), while granites, pegmatites, aplites, migmatites and orthogneisses have lower values (2.5–1.4 $\mu W.m^{-3}$) [39].

The geothermal energy of mine water is also dependent on the position of the mine in the regional groundwater cycle and the geothermal activity of the area [40,41]. The practically usable available power of geothermal energy of mine water was calculated to be 837.4 kW. In the case of continuous operation of the installed heat pumps at the assumed value of coefficient of performance (COP) 4, the theoretical production of almost 33,000 GJ of heat can be achieved per year, which exceeds the annual heat consumption of the northern part of the municipality of Dolní Rožínka several times over [30]. For the long-term life of the resource, a sufficient reserve of geothermal energy from the mining areas can be counted on, which was calculated to be 200,544 GJ according to the volume of excavated and flooded areas. This reserve makes it possible to use this resource for up to 44 years at the current consumption of 4350 GJ of heat per year.

3.2. Technical Model

The method of generating thermal energy from mine water is based on the use of circulating mine water through an open-cycle heat pump [42–44]. The circulation used depends mainly on the mine water quality, which must be decontaminated and discharged into the watercourse in a controlled manner. The starting parameter for the technical and economic model of mine water heat recovery is the statistical data for the total heat consumption of customers in Dolní Rožínka, which reaches an average 4350 $GJ.year^{-1}$ [29]. By distributing the total consumption into individual months according to the ratio based on statistics from 2016 to 2020 (see Table 2), it is necessary to consider the minimum consumption in the summer months and the maximum consumption in the winter months, where consumption peak power outputs of up to 750 kW heating capacity occur [27]. Table A1 precisely defines the technical terms used and Table A2 all used abbreviations.

Table 2. Total heat consumption by month for the period 2016–2020 [GJ] [29].

Year	1	2	3	4	5	6	7	8	9	10	11	12	Total
2016	887	603	595	338	165	64	51	59	86	404	653	739	**4643 GJ**
2017	1006	661	484	373	174	77	49	45	145	300	542	726	**4582 GJ**
2018	754	748	712	223	68	55	48	48	74	284	550	771	**4336 GJ**
2019	901	669	539	294	245	54	47	52	106	311	488	674	**4380 GJ**
2020	774	586	451	263	155	83	35	32	58	277	396	932	**4041 GJ**

The technology for heat and hot water production is designed with three options:

In Option 1, mine water is accumulated in a retention tank which is a part of the primary circuit and then transported through the secondary open circuit to the boiler plant heat pumps, where it transmits its heat and is further discharged into the watercourse. The heat produced by the heat pumps is then distributed to the individual buildings via the CDH system. The boiler plant also houses a backup heat source in the form of a gas boiler.

In Option 2, as in the previous option, the mine water is accumulated in a retention tank and then transported via the secondary open circuit to the boiler plant heat pumps, where it transmits its heat and is further discharged into the watercourse. The heat produced by the heat pumps is then distributed through the CDH circuit to individual buildings (mainly in the winter season), but it is also stored in an underground heat storage facility—borehole thermal energy storage mainly in the summer season, where it is then used to boost the heat supply in the winter. As in the previous option, a backup heat source in the form of a gas boiler is located in the boiler plant.

In Option 3, the primary circuit accumulates the mine water in a retention tank, and the secondary circuit transports it directly to individual heat pumps, which are installed separately at each heated building. Only the circulation pumps and the metering and control of the mine water flows are located in the boiler plant. The backups are solved by bivalent heat pumps at the buildings.

3.2.1. Primary Circuit

Mine water is pumped from the mine site to decontamination stations, where it is subjected to a decontamination process to remove insoluble substances, heavy metal elements and radioactive elements. At the output of the treatment process, the decontaminated water can be considered environmentally safe and, therefore, suitable for further use. During this process, the mine water is also heated from 10–12 °C to 16 °C, which represents a considerable financial saving.

The decontaminated water will be taken into the built retention tank located at the boiler plant in Dolní Rožínka through the built pipelines from the R1 and Bukov decontamination stations (DS) for a total length of about 4.5 km, see Figure 2. The proposed supply pipeline will consist of two branches: a northern branch from DS R1 of approximately 1.5 km and a southern branch from DS Bukov of approximately 3.0 km.

The grid is designed as standardized carbon welded steel pipework supplied in 6 m pieces and flange connected. The piping will be located below ground level below the frost line. A DN 200 diameter pipe with a wall thickness of 12.7 mm is considered [45].

Decontaminated water at 16 °C is assumed to be reduced by 5 °C, i.e., to 11 °C, due to losses during transport to the retention tank. This isolated retention tank will accumulate source water (see Figure 3). The proposed primary circuit is identical for all modelled options.

The key to the thermal energy recovery of pumped mine water is its temperature, flow rate, total supply and pumping timing. If the conditions of flooding half of the mine and resuming pumping are considered, i.e., the condition from 2024, then the R1 decontamination station (DS) will operate in continuous mode and have a discharge volume of 26 $L.s^{-1}$. The DS Bukov will also operate in continuous mode and have a discharge volume of 22 L.s^{-1}. Based on these facts, and taking into account the expected variations in pumping, a total pumped volume of 31.2 to 48.0 L.s^{-1} can be assumed, with a conservative mean value of 39.6 L.s^{-1}. In order to develop the technical model of the secondary circuit, it was first necessary to determine the input parameters, which are shown in Table 3.

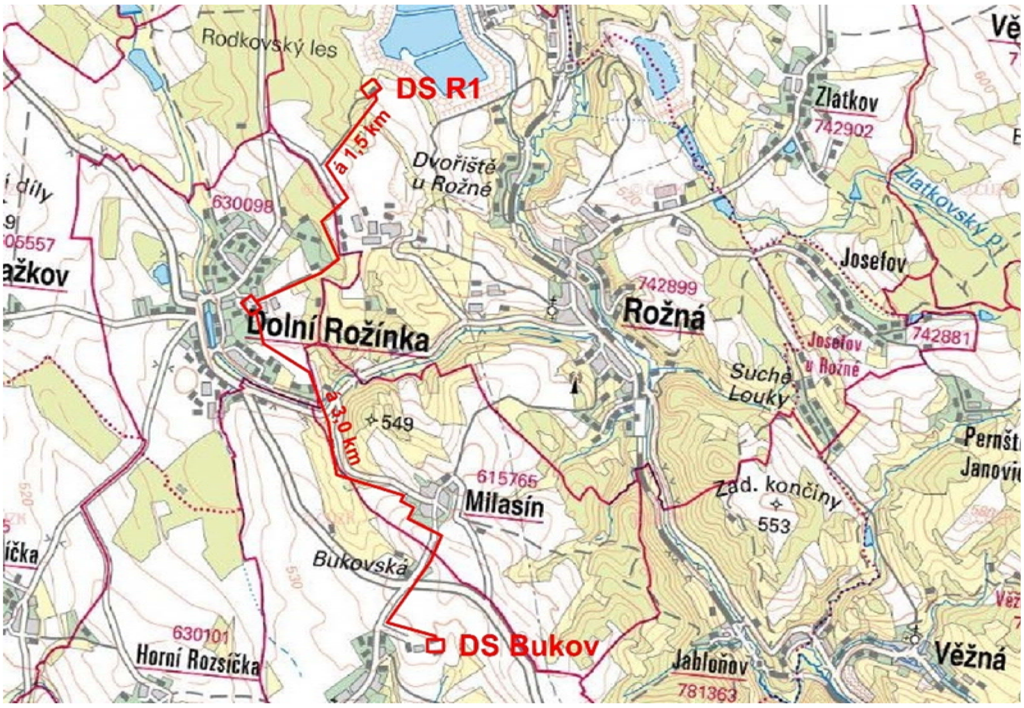

Figure 2. Proposed supply piping from the decontamination stations.

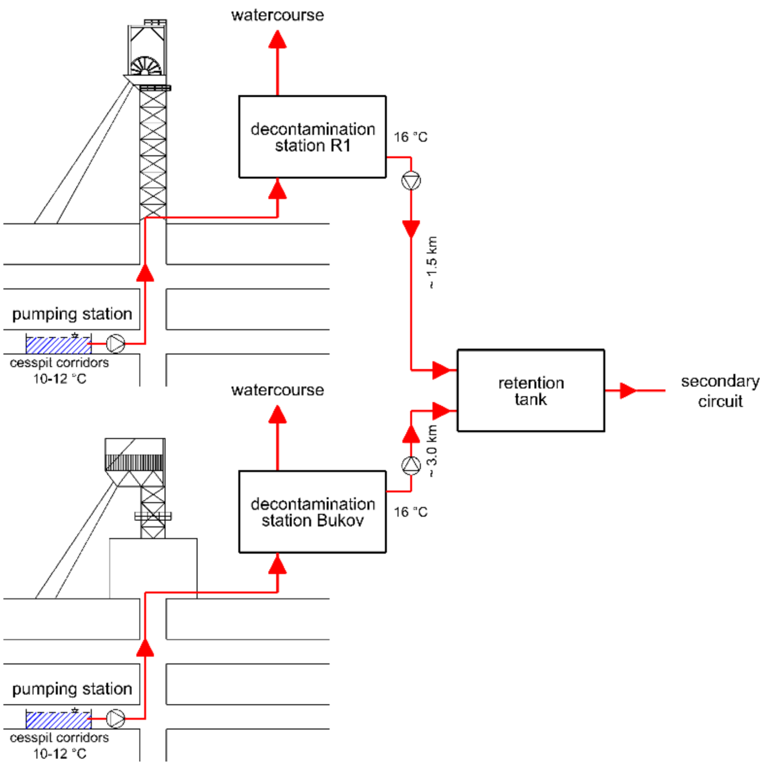

Figure 3. Schematic representation of the primary heat recovery circuit for decontaminated water.

Table 3. Summary of the parameters of the primary circuit of mine water heat recovery.

Parameter	Unit	Value
Min. total volume pumped per year	m^3	800,000.0
Max. total volume pumped per year	m^3	1,250,000.0
Min. instantaneous pumped volume	$l.s^{-1}$	25.4
Max. instantaneous pumped volume	$l.s^{-1}$	39.6
Temperature of mine water pumped from the mine	°C	12.0
Temperature of mine water at the outlet of the DS	°C	16.0
Temperature gradient for heat pump	°C	4.0
Minimum pumping period	year	20.0
Min. energy per year	GJ	13,382.4
Max. energy per year	GJ	20,910.0
Min. energy per year	kWh	3,720,307.2
Max. energy per year	kWh	5,812,980.0
Min. output	kWh	424.7
Max. output	kWh	663.6

From the above discussions, it can be concluded that it is possible to develop a technical model to provide heat supply from Rožná I Mine to Dolní Rožínka, Czech Republic.

3.2.2. Option 1: Central District Heating without BTES

Central district heating with the deployment of a central heat pump system considers the use of the existing infrastructure of the boiler plant in Dolní Rožínka, including its distribution network. Parallel heat pumps with a total capacity of 531 kW will be installed in the boiler plant. From the output of the heat pump, water at a temperature of 55–60 °C will be distributed through the existing distribution network to the end users in the northern part of Dolní Rožínka (see Figure 4). The cooled water will then be discharged into the local watercourse in a controlled manner.

The technical model was based on the following parameters:

- Heat pump operation ideally 3000 ± 10% hours;
- Peak power output 750 kW;
- Optimal heat pump performance such that the total annual operating efficiency is at least 75% while meeting the requirement of at least 67% peak power output and a COP of 4;
- The reconstruction of the boiler plant includes the renovation of the existing gas boiler as a backup;
- Heat pump temperature gradient 55/45 °C and flow rate 1.7–2 $L.s^{-1}$.

On the basis of the above, the optimization of heat production for Option 1 was assessed by comparing the heat production using the coefficient of available output of the heat pump (see Figure 5).

By comparing the annual heat production, according to the selected parameters, a coefficient of available output of the heat pump of 60% can be evaluated as the most suitable configuration, considering the following. A 50% coefficient of available output, while covering customer consumption more accurately and with lower production losses, cannot cover 67% of the peak power output (500 kW out of max. 750 kW) in the winter months. On the other hand, heat production at a coefficient of available output of 70% results in significant energy losses of up to 2306 GJ due to heat over production. Based on these facts, a 60% coefficient of available output has been assessed as the most appropriate as it can cover the peak power output demand in the winter months with acceptable energy losses of 1351 GJ. The operation of the heat pumps shall be adapted to the heat demand by introducing winter and summer operations. Heat production will be limited to domestic hot water supply only in summer operations. In winter operation, heat production will be standard.

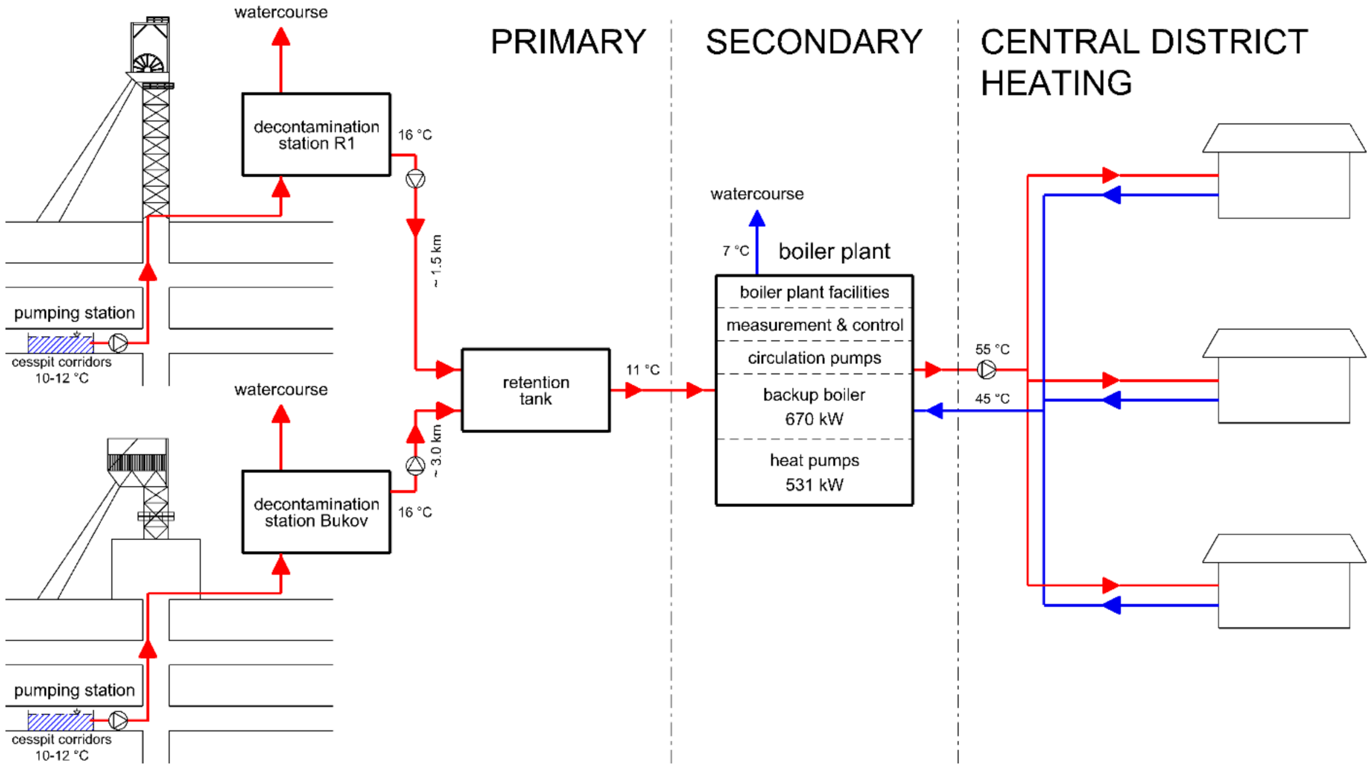

Figure 4. Schematic representation of Option 1 heat recovery of decontaminated water.

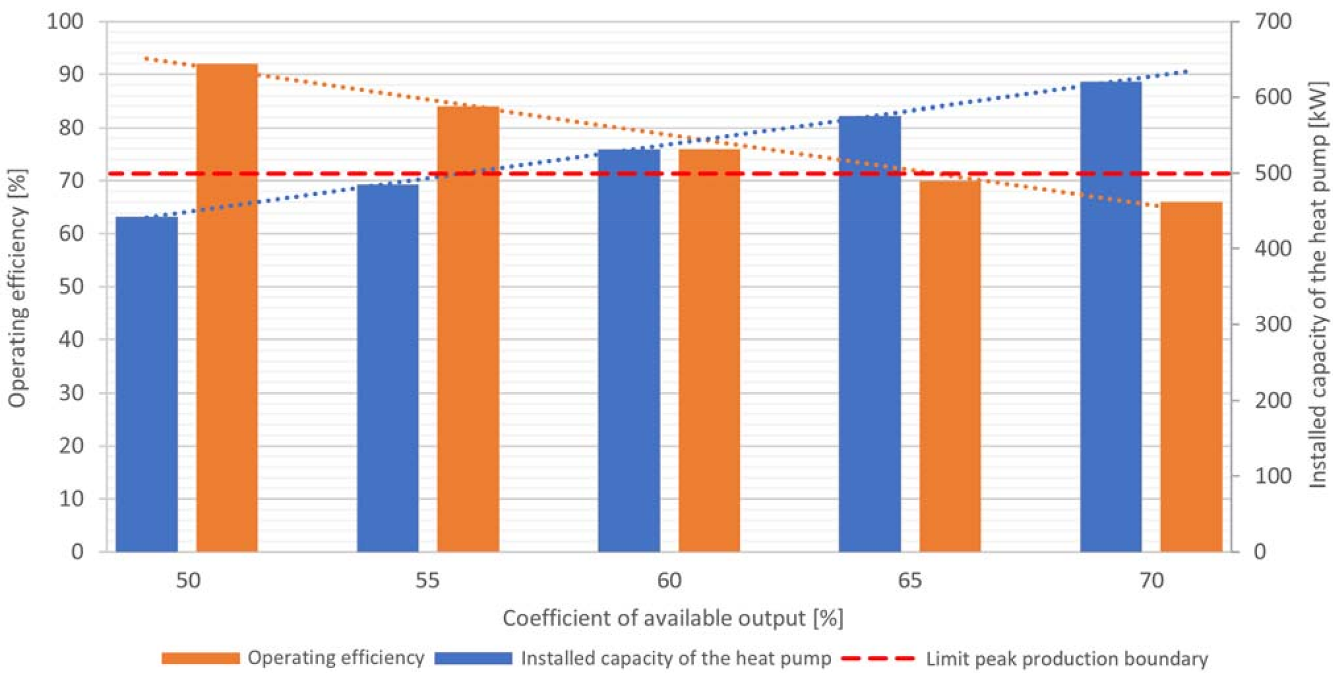

Figure 5. Comparison of heat production of Option 1 with the limit requirement for the heat pump output indicated.

One of the main disadvantages of this option is the difficulty of covering the fluctuations in outdoor temperatures and customer consumption during this period. The need to cover peak power output demand, which requires up to 0.75 MW of output during the winter months, leads to the installation of a gas boiler in the existing boiler plant as a backup source. The parameters of Option 1 are summarized in Table 4.

Table 4. Summary of Option 1 parameters.

Parameter	Unit	Value
Min. output	kWh	424.7
Max. output	kWh	663.6
Min. available output	kWh	254.8
Max. available output	kWh	398.1
Coefficient of available output of the heat pump	%	60.0
COP	-	4.0
Input power of the heat pump	kW_e	133.0
Heating output of the heat pump	kWh	531.1
Hours of the heat pump operation per year	hours	3007
Minimum annual production at 3000 h.year^{-1}	kWh	1,593,447.9
Minimum annual production at 3000 h.year^{-1}	GJ	5731.8
Operational efficiency	%	76.0

3.2.3. Option 2: Central District Heating with BTES

The central district heating with the deployment of a central system of heat pumps proposes, as in the previous option, to use the existing infrastructure of the boiler plant in Dolní Rožínka. Parallel heat pumps with a total capacity of 485 kW will be installed in the boiler plant. Subsequently, the same principles of heat transfer and water heating will be applied as in the previous Option 1, i.e., from 11 °C to 55–60 °C. This water will be distributed through the existing distribution network to the end users in the identified location. The cooled water will then be discharged into the local watercourse in a controlled manner. The difference with Option 1 is the modelled lower heat pump output and the construction of borehole thermal energy storage (BTES) (see Figure 6). The BTES can ensure continuous operation of the heat pump throughout the year with constant monthly production, better covering fluctuations in outdoor temperatures and, therefore, the instantaneous consumption by customers.

The BTES-type underground heat storage system considered in this option allows heat to be stored in the rock mass [46]. By being connected to the heating distribution system, the BTES acts as a conventional heat source, providing heat to the heated buildings and serves to cover the higher consumption during the winter months. The optimal yield of BTES is 60–80% [46,47]. By comparing the options according to the coefficient of available output of the heat pump, following the same principles as in Option 1 (see Figure 7) only the configuration with a 55% coefficient of available output and a simultaneous BTES efficiency of 64.1% can be determined as suitable.

The heat production configuration of Option 2 with a 55% coefficient of available output is based on an even distribution of the heat pump operation time over the months, thus achieving regularity of heat production and a uniform heat pump load. In the state of covering consumption only by production, the operation efficiency reaches 83%. However, the even distribution of operation results in only 52% of the consumption being covered in the month of January, for example. The operation of the heat pumps will be the same in all months of the year regardless of the season. In the summer months, the surplus produced will be stored in the BTES.

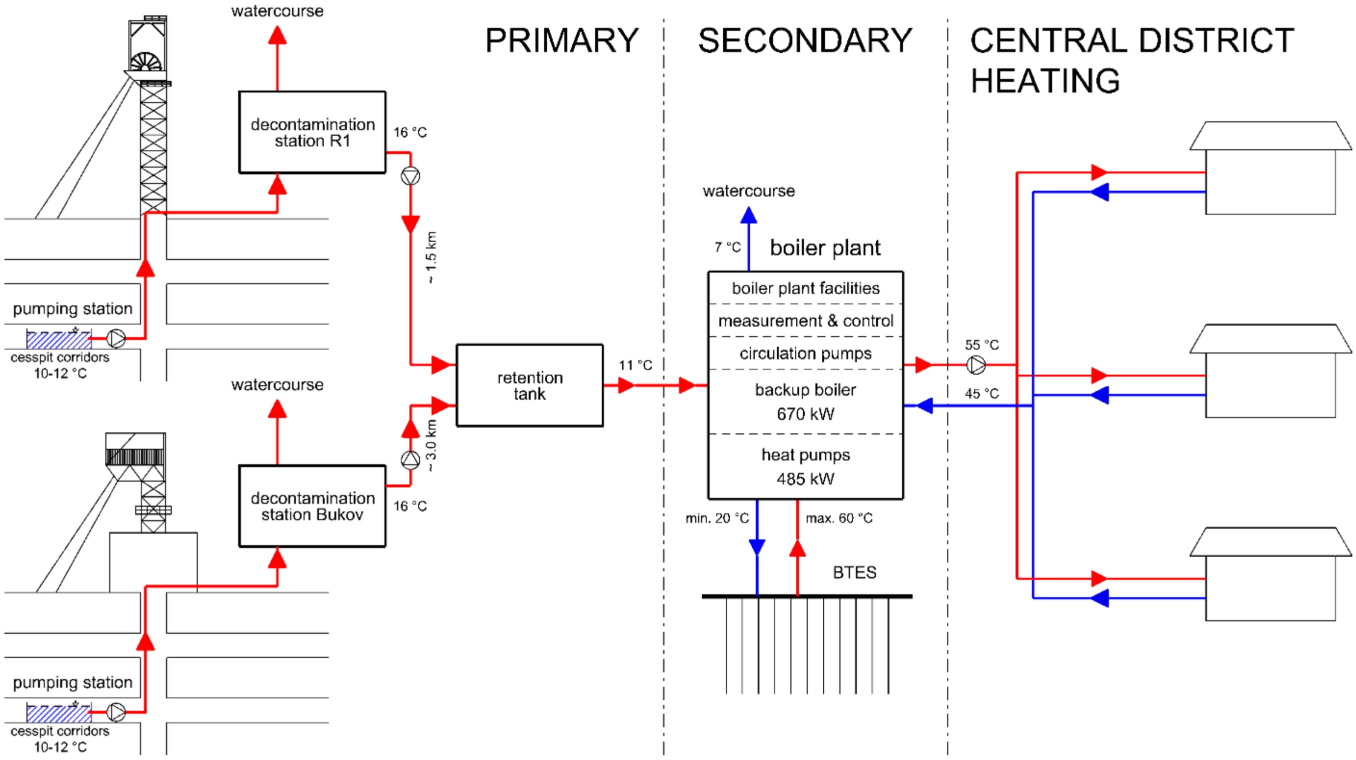

Figure 6. Schematic representation of Option 2 heat recovery of decontaminated water.

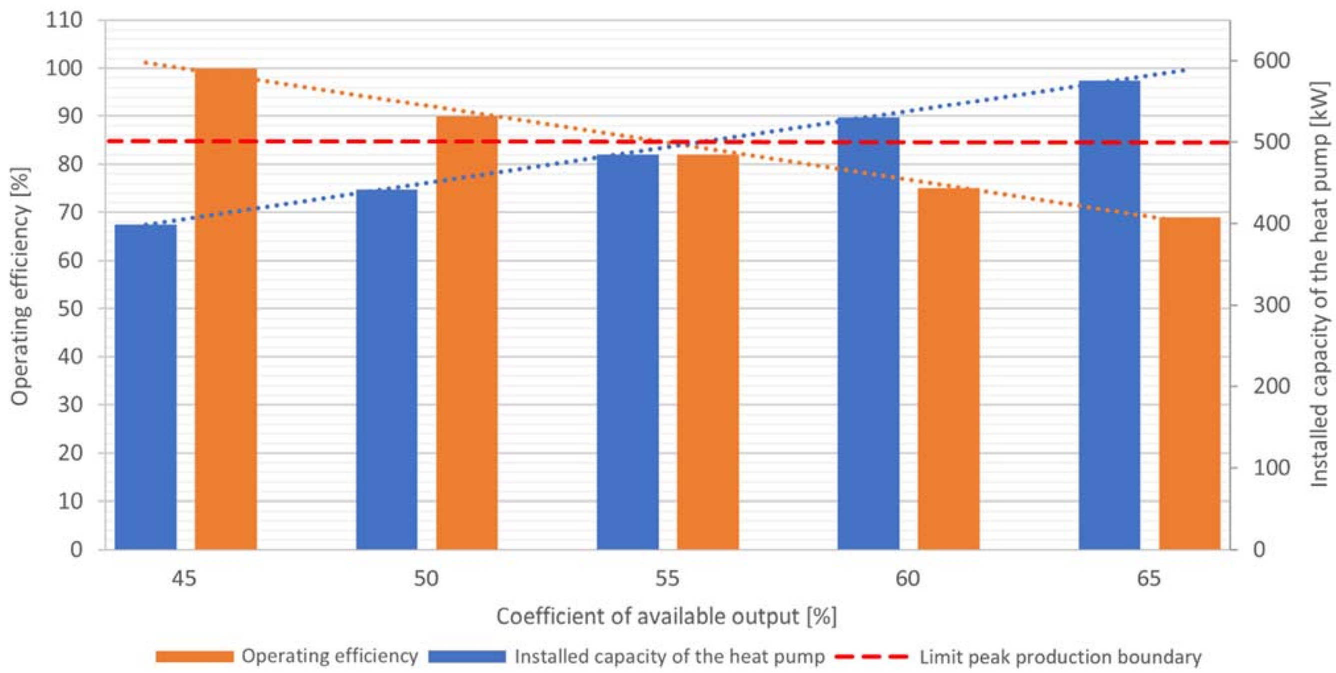

Figure 7. Comparison of heat production of Option 2 with the limit requirement for the heat pump output.

For this reason, it is first necessary to "fill up" the BTES underground heat storage during the first year of operation. In the following years, heat can be continuously extracted from this reservoir. It is represented in Figure 8 below.

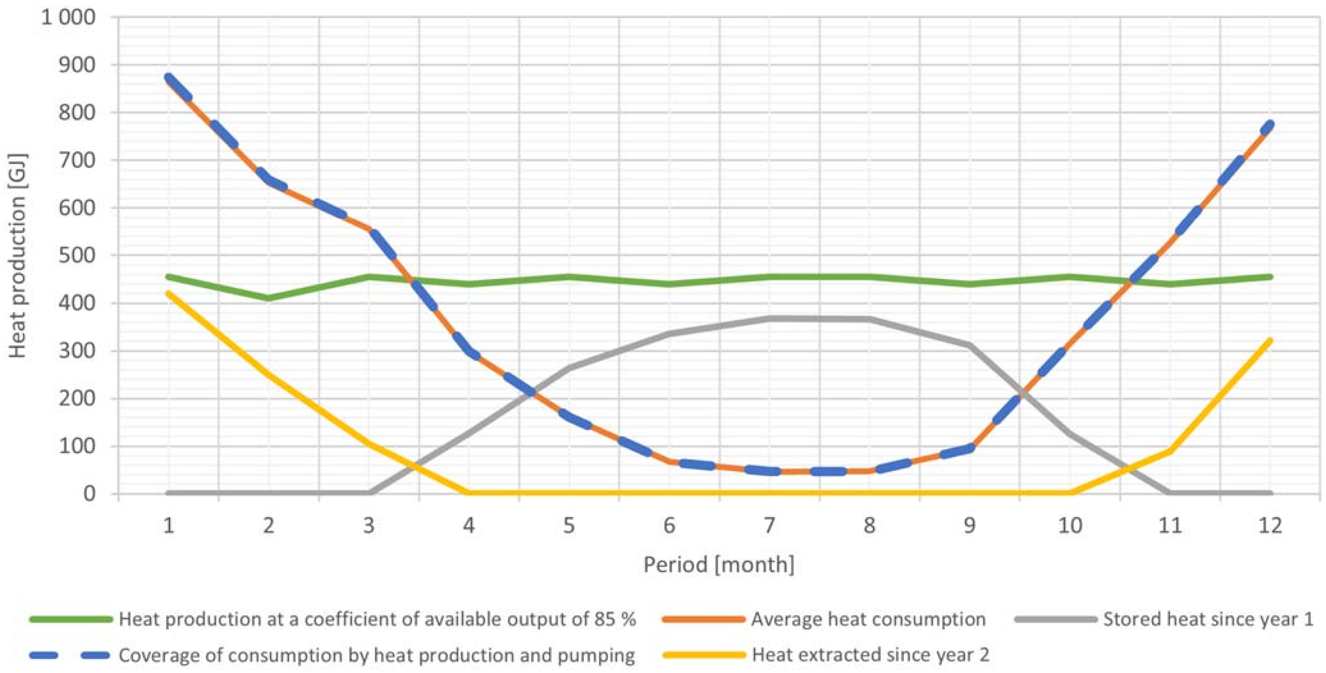

Figure 8. Heat production, storage and extraction of Option 2 by month.

Figure 8 shows that, in month 4, customer consumption falls below the production level. Therefore, any extra heat produced starts to be stored in the BTES underground heat storage. Here, it will be stored periodically in the period from month 4 to month 9. From the 10th to the 3rd month, the underground heat storage will be used to supplement the heat supply that standard production would otherwise not meet. Figure 8, therefore, shows the maximum overlap of the average heat consumption curve with the heat production and pumping curve and the minimum production losses.

Thus, once the operation is sufficiently up and running, i.e., once sufficient amount of heat is stored in the BTES, an average BTES efficiency of 64.1% can be achieved, and demand can be met continuously. In the event of peak power output demand, the underground heat storage will serve as a backup from which heat can be withdrawn at any time according to customer need. In combination with the underground heat storage, the condition of achieving 67% of the peak power output will not be met unconditionally. However, given the operational efficiency achieved, this shortcoming is negligible. At the same time, however, as in Option 1, a backup gas boiler must be installed in the boiler plant. Using an underground heat storage BTES makes it possible to reduce the output required for the heat pumps and, therefore, to use the minimum output values of the source. The model has verified that the optimum operation is at 55% coefficient of available output (see Table 5).

3.2.4. Option 3: Central District Heating with Individual Heat Pump Installations

This central district heating is represented by the installation of individual heat pumps at the point of heat consumption. By installing the heat pumps individually in each building, their operation can be designed and configured according to actual consumption (see Figure 9). Heat pumps will be installed at the end users according to the heating requirements of the building. The cooled water will then be discharged back to the boiler plant, where it will be discharged into the local watercourse as in previous cases. The backup source will consist of a bivalent heat pump design. For the purposes of the model, a 50:50 bivalence ratio is adopted. From the available statistical data on the specific consumption by individual customers from 2016 to 2020, it is necessary to design such a configuration so that the total heating capacity, including the reserve, is at least 400 kW [29]. The advantages of this option are the minimal cost of refurbishment of the existing boiler plant, flexibility in changing consumption, and the possibility of direct heating control by end users.

Table 5. Summary of Option 2 parameters.

Parameter	Unit	Value
Min. output	kWh	424.7
Max. output	kWh	663.6
Min. available output	kWh	233.6
Max. available output	kWh	365.0
Coefficient of available output of the heat pump	%	55.0
COP	-	4.0
Input power of the heat pump	kW_e	120.0
Heating output of the heat pump	kWh	485.0
Hours of the heat pump operation per year	hours	3066
Minimum annual production at 3000 $h.year^{-1}$	kWh	1,454,910.6
Minimum annual production at 3000 $h.year^{-1}$	GJ	5233.5
BTES efficiency	%	64.1
Operational efficiency	%	83.0

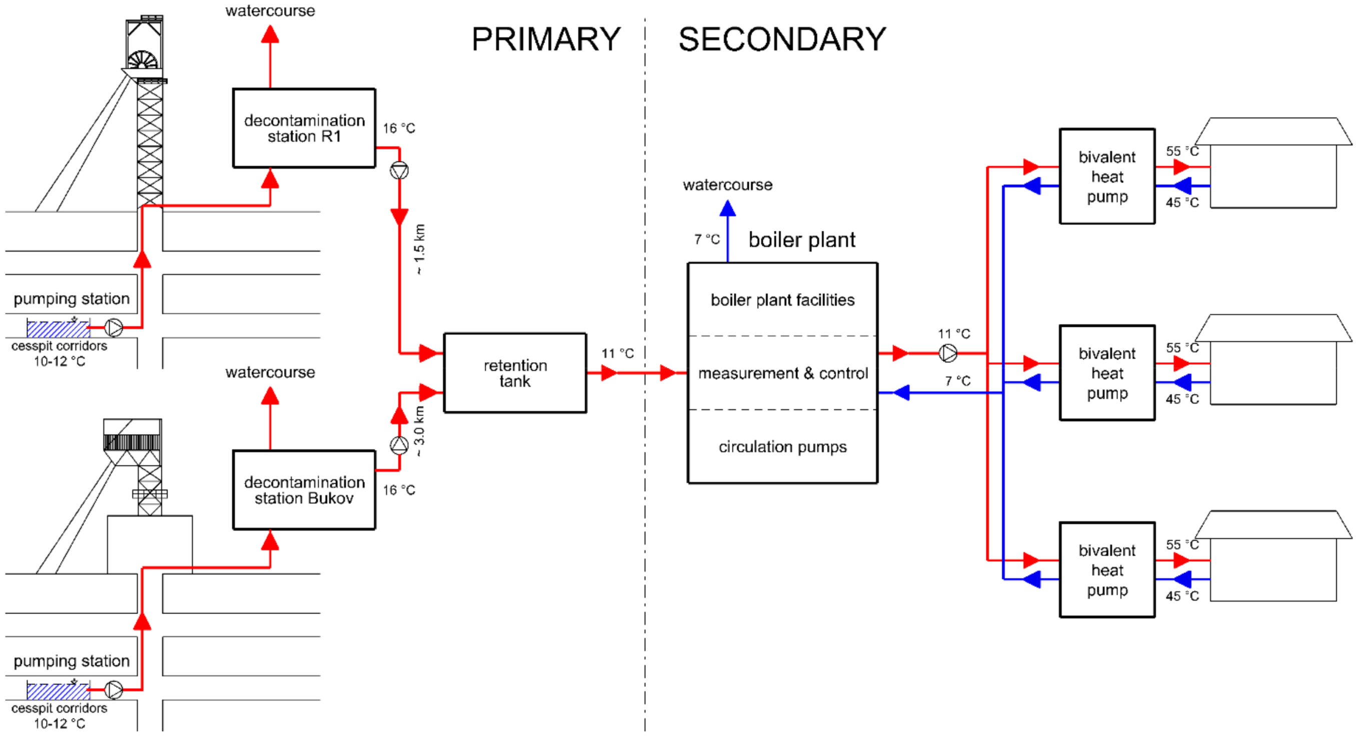

Figure 9. Schematic representation of Option 3 heat recovery of decontaminated water.

The technical model was based on the following parameters:

- Heat pump operation ideally 3000 ± 10% hours;
- Peak power output 750 kW;
- Optimal heat power output so that the total annual operating efficiency is at least 90%, while, at the same time, meeting the requirement of at least 50% peak power output and a COP of 4;
- Backups are created by the bivalent design of the heat pumps;
- The total heating capacity of the heat pump system is less than the minimum capacity calculated for the minimal flow of mine water, which is not a disadvantage;
- Heat pump temperature gradient 55/45 °C and flow rate 1.7–2 $L.s^{-1}$.

The technical model is based on the individual control of the individual heat pump outputs, which ensures more precise control of the individual heating modes of the buildings. The consequence of this approach is an overall lower required output and thus lower investment costs. As the required peak capacities for individual buildings are not known, the backup capacities to cover the peak power outputs are handled in the same way for all buildings by a 50:50 bivalence design. This, in turn, has a negative impact on operating costs. The operation of the heat pumps will be handled individually, and each heat pump in the buildings will have its own domestic hot water storage tank. The parameters of Option 3 are summarized in Table 6.

Table 6. Summary of parameters for Option 3.

Parameter	Unit	Value
Min. output	kWh	424.7
Max. output	kWh	663.6
Min. available output	kWh	191.1
Max. available output	kWh	298.6
Coefficient of available output of the heat pump	%	45.0
COP	-	4
Input power of the heat pump	kW_e	101.0
Heating output of the heat pump	kWh	400.0
Hours of the heat pump operation per year	hours	3215
Minimum annual production at 3000 $h.year^{-1}$	kWh	1,198,836.0
Minimum annual production at 3000 $h.year^{-1}$	GJ	4312.4
Operational efficiency	%	95.0

3.2.5. Comparison of Technical Options

Three technical options for the central district heating have been proposed. The technical options were designed in the most optimal operation mode with the specified operating conditions met. Option 1 presents traditional operation of central district heating. Option 2 is more efficient based on the addition of BTES to the system. Option 3 is the most efficient, because each object controls its own consumption. Table 7 summarises the main parameters of these options.

Table 7. The final comparison of the technical options.

Parameter	Unit	Option 1	Option 2	Option 3
Average consumption	$GJ.year^{-1}$	4350	4350	4350
Production	GJ	5746	5305	4622
Operational efficiency	%	76	83	95
Covering of peak power output	%	67	65	55
Backup for 750 kWh	-	gas boiler	gas boiler	bivalent heat pump
Coefficient of available output of the heat pump	%	60	55	45

3.3. Economic Model

Two main objectives emerge from the elaboration of the economic model of the above options. The first objective is to select, from the above options, the option that is relatively the most economically viable according to the chosen criteria. The second objective is to determine conditions under which the most appropriate option would be feasible for real investment.

For the comparison of the individual options, an interval of 20 years of operation for the heating system was chosen. On the basis of the estimated investment for each option, as well as the revenue and cost model, the cash flow from operating activities in each year was calculated, reduced by the assumed tax of 19% and discounted at a discount rate of 10%. The discounted cash flow values were used to determine three basic financial indicators for the investment projects, namely the simple payback period (SPP), the net present value (NPV) and the internal rate of return (IRR) [48–51]. It should be stressed that both the investment values and the values of the individual operating revenues and costs were estimated on an indicative basis, without in-depth analyses, tenders, evaluation of the costs of covering potential risks or third-party claims. The basic criterion for comparing the individual options is the necessary level of investment subsidy at which the given option will meet the required values of the mentioned investment evaluation indicators:

- SPP within ten years;
- NPV must be greater than zero (at a discount rate of 10%);
- IRR must be greater than or equal to 10%.

The investments required to implement the case study are only the basic items in the following range and are quantified in Table 8.

Table 8. Comparison of investments for each option (in CZK).

Item	Option 1		Option 2		Option 3	
	Quantity	**Total price**	**Quantity**	**Total price**	**Quantity**	**Total price**
Heat pumps	7.6 pcs	4,173,316	6.9 pcs	3,779,197	5.7 pcs	3,139,808
Piping from the source to the boiler plant	4500 m	4,950,000	4500 m	4,950,000	4500 m	6,750,000
Piping from the boiler plant to the buildings	1398 m	11,184,000	1398 m	11,184,000	1398 m	2,097,000
Circulation pumps from the source to the boiler plant	2 pcs	400,000	2 pcs	400,000	2 pcs	400,000
Circulation pumps from the boiler plant to the buildings	2 pcs	400,000	2 pcs	400,000	2 pcs	400,000
Heat exchanger in the boiler plant	1 piece	250,000	1 piece	250,000	0 pcs	0
Building modifications of the boiler plant	1 action	2,000,000	1 action	3,500,000	1 action	1,500,000
Measurement & control	2 sets	400,000	2 sets	400,000	2 sets	400,000
Underground heat storage tank	0 pcs	0	1 piece	3,000,000	0 pcs	0
Surface tank	0 pcs	0	1 piece	150,000	0 pcs	0
Total		**23,757,316**		**28,013,197**		**14,686,808**

Heat pumps—for simplicity of selection, a benchmark commercial heat pump of 70 kW was chosen to model the required performance. The solution is based on a real installation of a heating system at VSB-Technical University of Ostrava, where these modules are installed in 2x 700 kW capacity to heat two major buildings on the University campus [52,53].

Pipeline from the mine water source (decontamination station) to the boiler plant (Option 1 and 2) or directly to the foot of the heated buildings (Option 3)—the total length of the pipeline considered in this way is 4500 + 1400 m. The prices used were derived from the usual unit prices for the construction of this type of water supply infrastructure in the Czech Republic [53]. This does not include the cost of potential conflicts of interest or technical risks (e.g., costly overcoming of natural obstacles). This item has a high degree of volatility, but this uncertainty is the same for all options and does not affect the actual relative comparison of the options.

Piping from the boiler plant to individual buildings—this consists of pre-insulated piping considered only in Options 1 and 2 in the existing route. The cost is based on a professional estimate from the local company currently operating the boiler plant [54].

A technical modification of the boiler plant, for Options 1 and 2, including the backup source—the costs for the reconstruction of the boiler plant are also estimated by local specialists, as in the previous case, with the backup source (Options 1 and 2) consisting of the existing gas boiler, which would undergo an overhaul [55]. The cost of the overhaul is included.

Circulation pumps, heat exchangers and metering and control—in the context of the overall investment, these are insignificant items whose technical scope and cost are almost the same for all options.

BTES underground heat storage—this is based on the research and development installation of underground heat storage in the building of Green Gas DPB, a.s. in Paskov (Czech Republic), which was installed in cooperation with VSB-Technical University of Ostrava [56,57]. This reservoir has comparable storage capacity and comparable efficiency under comparable geological and hydrogeological conditions. The technical solution is 16 boreholes to a depth of 60 m. The total cost is based on this assumption.

Costs do not include the cost of pumping mine water from the mine pumping stations to the surface to the decontamination stations. These expanses are included in the operating costs of the state-owned mining enterprise DIAMO.

The model assumes that the sources of investment are a combination of owned resources and interest-free investment subsidies. The annual operating revenues were determined as the product of the units sold (GJ) in a given year and the price per unit. The number of units sold was modelled the same in each year. This value corresponds to the average of the actual units sold over the past five years. The price per unit was set as the real current price in the first year and then escalated by 2% each year after that, considering the expected increase in the market price of energy.

In terms of operating costs, the cost of the electricity required to power the heat pump compressors represents the major variable. With a calculated COP of 4, the annual cost is calculated as the product of the kWh required and the current unit price per kWh in the heat pump tariff in the Czech Republic. This category also includes the cost of the electricity required to drive the circulation pump motors and the metering and control elements of the system. Other operating costs are then made up of the operation and maintenance costs of the plant, which are set at a flat rate, which is the same for all options. The provision is set as a one-off item for Options 1 and 2. In Option 3, this item is increased to cover possible extra electricity costs when using the backup of the bivalent heat pumps.

The results of the modelling are summarized in Table 9 below.

Table 9. Modelling results.

Option	Total Investments	SPP Years	NPV	IRR%	Amount of Investment Subsidy
1	23,757,316 CZK	10	126,672 CZK	10%	19,500,000 CZK
2	28,013,197 CZK	10	122,184 CZK	10%	23,000,000 CZK
3	14,686,808 CZK	10	262,360 CZK	11%	11,850,000 CZK

Option 1 achieves the highest performance with the lowest operation efficiency and requires the necessary installation of pre-insulated piping from the boiler plant to the buildings. In terms of the economic model, it is the second in order. On the other hand, Option 2 has lower outputs, with a higher operation efficiency compared to Option 1. The loss in output, i.e., lower investment costs for heat pumps, is technically solved by the construction of a BTES, which, however, requires investments higher than the savings resulting from fewer heat pumps. For this reason, Option 2 is assessed as the worst economic option. Option 3 does not consider pre-insulated piping between the boiler plant and the individual buildings. Therefore, the investment required is significantly lower. At the same time, the calculated total power required is the lowest and the efficiency the highest, based on the assumption that the control of individual smaller units is more operation efficient. On the other hand, higher operating costs for electricity covering the bivalency backup are necessary. Nevertheless, this option is the most economically advantageous of the three options examined.

4. Conclusions

The case study models the industrial use of the geothermal potential of mine water from the Rožná deposit with a temperature of 16 °C for the central district heating of inhabitants in the northern part of the municipality of Dolní Rožínka. Currently, district heating is provided by a central gas boiler plant, which is no longer capable of operating profitably. This boiler plant requires significant reconstruction or modification to maintain the current requirements for heat supply to the contracted buildings in private or municipal ownership. In view of the positive conclusions of the mine water availability analysis, the Rožná deposit has been assessed as a suitable alternative and environmentally friendly source of energy for heat supply.

On the basis of the above, three possible options for the implementation of the central district heating system were developed. For these options to be implemented, it is necessary to build a supply pipeline from the mine water source to the boiler plant, where a retention tank can be set up to ensure continuous supply to the heat pumps. In the case of Options 1 and 2, the heat pumps are installed in parallel in the area of the modified gas boiler plant. From there, the heated water is distributed via insulated pipes to the customers' premises. This option can be modified with an underground heat storage BTES (Option 2), which would achieve a more continuous heat supply with significantly lower production losses. The third option considers a heat supply system with mine water distribution directly to the foot of the individual buildings. Here, the heat will be exchanged in individual heat pump installations.

To evaluate financial viability of the models, three underlying assumptions have been defined: NPV higher than 0; IRR higher than 10% and SPP up to 10 years. Taking these parameters into consideration, all three financial models are in compliance with these requirements. Thus, in this simplified financial calculation, the level of financial support is a crucially determining indicator. The values of support 19.50 million CZK for the first option, 23.00 million CZK for the second option and 11.85 million CZK for option number three show the most beneficial technical solution.

Comparing the relative results of the economic model, the selection of Option 3 is the most favorable in relation to this case study. Although the input values of investments, revenues, and costs have been estimated in an indicative manner, it is clear from the calculations that none of the options would be economically viable without investment or, possibly, other investment subsidies. In terms of current heat demand, the central supply system appears to be relatively small. The fixed costs of installation and operation at regulated energy prices and at the number of GJ units sold per year are thus too high. A different situation would arise if the full potential of potential customers was used and sales were increased by 50%. Then, the economy of the whole project would meet the parameters set in Option 3, almost without subsidies.

Given the uniqueness of using the thermal potential of pumped mine water for the needs of the central district heating of Dolní Rožínka, the following results of the case study can be summarized: (i) of the possible technical solutions, the most economically advantageous option is likely to be the one in which mine water, as a primary source of thermal energy is fed directly to the foot of individual heated buildings to heat pumps of the appropriate capacity; (ii) even this option requires a considerable investment subsidy, which could be significantly reduced provided that the currently existing potential of customers is connected to intake, which will increase sales by about 50% per year.

Author Contributions: Conceptualization, M.V. and A.K.; Methodology, A.K. and M.V.; Formal Analysis, M.V.; Investigation, M.V. and A.K.; Data Curation, M.V.; Project Administration, M.V.; Visualization, M.V.; Resources, M.V., Writing—Original Draft Preparation, M.V. and A.K.; Writing—Review and Editing, A.K. and M.V., Supervision, A.K. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would like to acknowledge the financial support of the Ministry of Education, Youth and Sports of the Czech Republic under the project SP2021/10 "Analysis of the using of the energy potential of mine water for central heat supply".

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Statistical data on the production and consumption of heat of the boiler room in Dolní Rožínka were obtained from SATT company and are available from the authors with the permission of SATT company.

Acknowledgments: The authors would like to thank the Editor and the anonymous reviewers for their insightful comments and suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Interpretation of terms.

The Term Used	Interpretation
primary circuit	section from the mine water source to the retention tank
secondary circuit	section from the retention tank to the boiler plant
central district heating (CDH) circuit	section from the boiler plant to individual buildings
boiler plant	central building with essential technical equipment
central district heating backup source	backup gas boiler located in the boiler plant
backup source of heat pump equivalent	heat pump installed in the building (not in the boiler plant)
coefficient of performance (COP)	indicates the ratio of heat produced to energy consumed
average annual heat consumption	statistical value based on actual heat consumption from 2016–2020
heat price	average heat price at the study site in 2020
electricity price	average electricity price on the market in the Czech Republic for 2020 in the tariff for the heat pump
optimum number of the heat pump operating hours per year (with deviation)	indicates the manufacturer's recommended range of use for proper operation of the heat pump
coefficient of available output of the heat pump	indicates the ratio of the heat pump output in relation to the theoretical maximum possible output (max. output)
max. output	calculated parameter indicating the maximum achievable output at the maximum mine water flow rate
min. output	calculated parameter indicating the minimum achievable output at the minimum mine water flow rate
peak power output	power required to cover peak demand of Dolní Rožínka municipality in winter
operational efficiency	indicates the ratio of heat produced to heat consumed per year at the locality
BTES efficiency	indicates the ratio of thermal energy extracted from the BTES to the thermal energy stored in the BTES per year

Table A2. List of abbreviations.

The Abbreviation used	Interpretation
BTES	Borehole Thermal Energy Storage
CDH	Central District Heating
COP	Coefficient of Performance
DS	Decontamination Station
IRR	Internal Rate of Return
NPV	Net Present Value
SPP	Simple Payback Period

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