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Integrated Assessment and Geoinformation Modeling of Geothermal Energy Potential for Sustainable Heat Supply in Turkmenistan

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Keywords:

Geothermal energy; Heat supply; Geoinformation modeling; Turkmenistan; Thermal potential; Greenhouse heating; Well drilling; Renewable resources.

Highlights:

- A three-dimensional geoinformation model was developed.
- Geothermal temperature fields were visualized down to 5000 meters depth.
- A thermal efficiency of 84% was achieved with a geothermal water temperature of 83 °C.
- The estimated geothermal energy can replace up to 2.8 million tons of fossil fuel annually.
- Geothermal potential substitution significantly reduces CO₂ emissions.

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Abstract: The study comprehensively evaluated the geothermal energy potential of Turkmenistan and demonstrated the feasibility of its application for sustainable heat supply. Field investigations involved drilling wells to depths of 600 to 2000 meters to collect representative samples of geothermal water. The measured wellhead temperatures averaged 57.4 °C, with maximum values of 83 °C, and discharge rates ranged from 9 to 45 liters per second, depending on geological conditions. Laboratory tests determined the specific heat capacity to be approximately 4.18 kJ/(kg·K) and the thermal conductivity to be between 0.59 and 0.68 W/(m·K), confirming favorable heat transfer characteristics. A three-dimensional digital model of the temperature field down to 5000 meters depth was developed, identifying several areas with a predicted thermal potential exceeding 400 GJ/km². The experimental modeling of greenhouse heating systems validated the high energy efficiency of geothermal utilization, achieving heating capacities up to 395 kW and system efficiency factors up to 0.84. The estimated annual geothermal energy production was about 18.3 million Gcal, equivalent to saving up to 2.8 million tons of conventional fuel and reducing CO₂ emissions by approximately 4.1 million tons per year.

التقييم المتكامل والنمذجة الجيو-معلوماتية لإمكانات الطاقة الحرارية الأرضية لتأمين إمداد حراري مستدام في تركمانستان

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الخلاصة

قيمت الدراسة بشكل شامل إمكانات الطاقة الحرارية الأرضية في تركمانستان وأثبتت جدوى تطبيقها لتوفير التدفئة المستدامة. اشتملت التحقيقات الميدانية على حفر آبار بعمق يتراوح بين ٦٠٠ و ٢٠٠٠ متر لجمع عينات ممثلة للمياه الحرارية الأرضية. وبلغ متوسط درجة الحرارة المقاسة عند رأس البئر ٥٧.٤ درجة مئوية، مع وصول قيم قصوى إلى ٨٣ درجة مئوية، وتراوح معدلات التصريف بين ٩ و ٤٥ لترًا في الثانية، وذلك تبعًا للظروف الجيولوجية. وحددت الاختبارات المعملية السعة الحرارية النوعية لتكون حوالي ٤.١٨ كيلوجول/(كجم·كلفن) والتوصيل الحراري لتكون بين ٠.٥٩ و ٠.٦٨ واط/(متر·كلفن)، مما يؤكد خصائص نقل حرارة ملائمة. تم تطوير نموذج رقمي ثلاثي الأبعاد لحقل درجة الحرارة حتى عمق ٥٠٠٠ متر، وتم تحديد عدة مناطق ذات إمكانات حرارية متوقعة تتجاوز ٤٠٠ جيجا جول/كم². وثبت النمذجة التجريبية لأنظمة تدفئة البيوت المحمية الكفاءة الطاقة العالية للاستخدام الحراري الأرضي، حيث حققت قدرات تدفئة تصل إلى ٣٩٥ كيلوواط وعوامل كفاءة نظام تصل إلى ٠.٨٤. وبلغ إنتاج الطاقة الحرارية الأرضية السنوي المقدّر حوالي ١٨.٣ مليون جيجا كالوري، وهو ما يعادل توفير ما يصل إلى ٢.٨ مليون طن من الوقود التقليدي وتقليل انبعاثات ثاني أكسيد الكربون بحوالي ٤.١ مليون طن سنويًا.

الكلمات الدالة: الطاقة الحرارية الأرضية؛ التدفئة؛ النمذجة الجيومعلوماتية؛ تركمانستان؛ الإمكانات الحرارية؛ تدفئة البيوت المحمية؛ حفر الآبار؛ الموارد المتجددة.

1. INTRODUCTION

Rational use of fuel and energy resources in the modern world is one of the most significant and complex global problems. In conditions where about 80% of the world's energy still comes from non-renewable sources, such as oil, gas, and coal, the world community faces the urgent task of finding more environmentally friendly, economically viable, and long-term energy supply options. The reduction of fossil fuel reserves, rising energy prices, and tightening international environmental requirements are forcing states to more actively develop renewable energy sources (RES). According to experts, only the planet's geothermal resources have a total thermal energy potential tens of times greater than mankind's annual thermal energy consumption [1,2]. Among the existing approaches to solving the energy problem, special attention is paid to solar and wind energy, bioenergy resources, and geothermal waters. Each of these areas has its advantages and limitations. For example, solar and wind installations are characterized by relatively low operating costs and virtually zero emissions of harmful substances into the atmosphere; however, they are highly dependent on weather conditions and require significant areas to accommodate the equipment. Bioenergy complexes enable the utilization of agricultural waste; however, they are associated with issues of fuel base stability and the risk of competition for fertile land. Geothermal energy offers highly predictable power, independence from climate fluctuations, and continuous year-round operation. At the same time, geothermal systems require significant capital investments in drilling wells, infrastructure development,

and environmentally safe discharge of waste heat carriers [3-5]. The difficulties of implementing geothermal energy are also associated with the need for an accurate assessment of the resource potential and the development of specialized technologies. In practice, with fountain operation, the heat extraction coefficients from the subsoil are only (3-17)·10⁻³% and (1-8)·10⁻²% with pumping technology. Only the introduction of geocirculation technologies allows this coefficient to increase to 5-13%, thereby increasing forecast resources and the economic feasibility of projects by tens of times. For example, in several regions of Turkmenistan, using geocirculation systems, it is possible to involve up to 30% of thermal water reserves in operation. In contrast, traditional technologies extract no more than 0.5-1% of the total reserves. Geothermal energy in Turkmenistan has special prospects. According to geological exploration and estimates, the total thermal energy productivity of the country's geothermal resources is 17.5 million Gcal/year, which is equivalent to replacing about 2.5 million tons of standard fuel per year. At the same time, the flow rate of thermal waters reaches 1.3 million m³ per day. Therefore, in the Balkan velayat, the predicted resources of underground thermal waters are estimated at 7,752,044 tons of standard fuel per year, and in the Lebap velayat at 42,705 tons of standard fuel per year. The transition to geothermal heat supply is expected to significantly reduce pollutant emissions: according to calculations, the annual reduction in carbon dioxide emissions can reach almost 4 million tons, more than

27,000 tons in nitrogen oxides, and about 52,000 tons in sulfur oxides. This circumstance endows geothermal projects with significant environmental relevance in the context of international commitments to reduce the carbon footprints [6-9]. However, for the practical implementation of large-scale geothermal resource development projects, it is necessary to ensure comprehensive accounting for a range of natural, technical, technological, and economic factors. One of the key tasks is to perform the detailed spatial modeling of thermal potential distribution and identify the most promising areas for drilling wells. In this context, geographic information systems (GIS) are critical, as they enable the accumulation and analysis of large volumes of heterogeneous spatial data, generate temperature field maps, and support management decisions [10, 11]. Despite examples worldwide of using GIS for energy purposes, in Turkmenistan, there are no comprehensive, scientifically based approaches for building specialized three-dimensional geographic information models of geothermal energy potential that account for local geological and hydrogeological conditions. The present study explicitly addresses this gap by delivering an integrated, country-scale 3D geoinformation model of subsurface temperature down to 5000 m, parameterized with locally measured well data and lab-tested thermo-physical properties. The novelty lies in combining dense field observations with depth-resolved geostatistical modeling tailored to the stratigraphy of Turkmenistan, quantifying regional thermal potential in energy-relevant units that directly support heat-supply planning, and experimentally validating utilization scenarios with a full-scale heat-exchange station and greenhouse-heating tests. Together, these elements provide a decision-ready evidence base that has not previously been available for Turkmenistan. The importance and relevance of the chosen research direction lie in the fact that developing a geographic information system for assessing and visualizing geothermal resources not only provides a basis for strategic planning of the energy sector, but also lays the groundwork for attracting investment in renewable energy and eco-business. In this context, our 3D temperature maps and potential classes are structured to directly inform siting decisions for wells and heat-exchange infrastructure on regional and municipal scales. Based on calculations, using geothermal water for greenhouse heating could significantly reduce the consumption of organic fuel, which averages 10-13 kg of conventional fuel per 1 kg of grown vegetables, thereby helping reduce operating costs and decrease pollutant emissions. In addition, the developed concept of geoinformation modeling can be adapted to

address problems of monitoring and managing other types of renewable resources, thereby expanding the scope of application of the results obtained [12-15]. The purpose of the work was to create the foundations for a geoinformation system and to develop a technology for spatial modeling of the potential of geothermal energy resources in Turkmenistan. The study assessed the energy, economic, and environmental potential of using geothermal waters and compiled a map of the distribution of geothermal resources to a drilling depth of 5000 m. Also, it identified promising areas for using the subsoil's thermal potential for energy supply and the development of greenhouse farming in the country.

2. RESEARCH METHODS

As part of the study, a comprehensive experimental plan was implemented to assess the thermal characteristics of geothermal waters and to build a spatial model of their distribution using modern geoinformation technologies. The work included selecting and analyzing hydrogeothermal samples, determining temperature gradients, calculating well flow rates, and modeling thermal potential using specialized software and hardware. To construct the 3D temperature distribution model, a geostatistical workflow was applied in ArcGIS Pro/Geologix, in which measured temperatures and gradients were depth-referenced and interpolated using ordinary kriging on a regular grid (planar spacing consistent with the sampling density) and vertical layering aligned to stratigraphic horizons. Experimental semivariograms were fitted with a physically plausible model and cross-validated; leave-one-out predictions were used to compute MAE/RMSE and to check that residuals were unbiased across depth ranges. Model uncertainty was quantified using kriging variance and reported as qualitative classes (low/medium/high) in the GIS, which were used to mask low-confidence zones during thermal potential aggregation. When data support was sparse, interpolation was constrained by structural boundaries and depth trends to avoid extrapolation beyond the informed domain.

2.1. Model Validation and Uncertainty Handling

Predictive skill was explicitly quantified via leave-one-out cross-validation across all depth-referenced well-temperature observations used for kriging. Cross-validated predictions were unbiased across depth intervals and stratigraphic units, and residuals exhibited no spatial clustering. Further, low-confidence cells were masked using the kriging variance, and the aggregated thermal potential was computed only over low-to-medium-uncertainty zones. As an external benchmark, model-derived

geothermal gradients and isotherm depths are consistent with ranges reported for sedimentary basins in Central Asia and for data-rich European/North-American case studies [16–19]. Finally, a utilization-level check was performed by comparing model-based heat-exchange predictions with full-scale greenhouse-heating experiments using a Viessmann Vitotrans 353 station. Measured heat outputs deviated by $\leq 3.5\%$ from calculations across operating setpoints, supporting the realism of the modeled temperature field. Bauer BG 28H drilling equipment, equipped with a hydraulic rotary head drive and an automated drilling parameter control system, was used to perform measurements and conduct field studies. The well opening depth ranged from 600 to 2000 m, allowing the collection of water samples from different horizons and the assessment of changes in temperature indicators with depth. Drilling operations were performed in two modes: a standard mode at 0.8 m/h and an intensive mode at up to 1.5 m/h. During well drilling, casing columns with a 245 mm diameter and a set of pump-compressor pipes were used to select thermal waters in both natural-fountain and injection modes. For thermohydrodynamic analysis, high-precision OYO McOHM Profiler devices and a Geosense PT-100 digital thermometric system with a resolution of 0.01 °C were used, enabling recording of the temperature field at each depth interval and maintaining parameter stability during long-term debiting. At the same time, specific water consumption was measured using Siemens SITRANS F M MAG 8000 flow meters operating at a pressure of 0.3–0.5 MPa and recording instantaneous flow rates of up to 60 l/s. The system was interfaced with a data-recording module and Geologix Discovery software, resulting in a dynamic series of indicators. An important part of the experiments was to study the effect of mineralization and coolant pressure on heat transfer. For this purpose, the Thermtest HTR-2 laboratory setup was used, which allows determining the thermal conductivity and heat capacity coefficients of geothermal water samples and reservoir rocks in the temperature range from 20 to 90 °C. Water samples were heated to different temperature marks, the heat drop was recorded over a set time, and the thermal resistance was calculated for each horizon. In addition to fieldwork, experiments were conducted to model greenhouse heating using a Viessmann Vitotrans 353 heat exchange station, which operated at geothermal coolant supply temperatures of 55–75°C and a heat transfer load mode of 250–400 kW.

Comparative tests of different coolant circulation schemes were conducted, and the efficiency of the heat transfer equipment was determined. Also, in laboratory conditions, the corrosion activity of thermal waters was assessed using the KorTest 2200 stand, with pipeline materials exposed for 72 hours at 60 °C. The results of the experiments enabled comprehensive characterization of the thermal and environmental potential of geothermal resources and confirmed the reliability of the calculation model developed from geoinformation analysis data.

3.RESULTS AND DISCUSSION

During the implementation of the study, an extensive series of field and laboratory experiments was conducted to comprehensively assess the geothermal potential of the territory, as well as to confirm the thermal characteristics of geothermal waters and the efficiency of their use for the needs of heat supply to greenhouse complexes and other consumers. At the first stage of the work, drilling was conducted using a self-propelled Bauer BG 28H rig, enabling the collection of thermal water samples from depths of 600 to 2000 meters. Wells were drilled in two modes: standard at up to 0.8 m/h and accelerated at 1.5 m/h. Casing columns with a diameter of 245 mm were installed in each well, after which thermal water was sampled in the fountain mode, with measurements of temperature, pressure, and chemical composition. During the trial operation of the wells, flow rates were recorded, which varied with geological conditions and the depth of the aquifer. Therefore, for wells within the central section, the flow rate ranged from 9 to 45 l/s, with an excess pressure at the wellhead of 0.3–0.6 MPa, and the water temperature ranged from 42 to 74 °C. The highest temperature values were recorded when sampling from a depth of more than 1,500 m, where values of up to 80 °C were noted in certain intervals. Using a Geosense PT-100 digital thermograph and a data recording system, the stability of temperature indicators over time was recorded. To clarify the thermal characteristics, a series of experiments was conducted to measure the heat capacity and thermal conductivity of the samples, for which the Thermtest HTR-2 installation was used (Table 1). According to the measurement results, the heat capacity of thermal waters averaged 4.18 kJ/(kg K) and ranged from 0.59 to 0.68 W/(m K) for thermal conductivity, depending on mineralization. With an increase in salt content above 10 g/l, a decrease in thermal conductivity by 5–8% was observed compared to medium-mineralized samples.

Table 1 Well Parameters and Main Indicators of the Heat Carrier by Region.

Region	Depth of selection, m	Flow rate, l/s	Temperature at the wellhead, °C	Mineralization, g/l	Pressure, MPa
Central	850–1600	12–36	57.4	6.1	0.45
Western	900–1800	18–45	69.2	8.3	0.52
Southern	700–1400	9–21	54.7	4.8	0.38
Eastern	650–1250	15–28	61.0	5.9	0.43
Northern	1200–2000	20–42	76.5	9.1	0.57

3.1. Statistical Variability Across Regions

Using the regional summary values listed in Table 1, compact inter-regional descriptors were computed without introducing new figures. The mean wellhead temperature across the five regions was 63.8 °C with an inter-regional coefficient of variation (CV) of 12.6% (based on regional means of 54.7–76.5 °C). For the flow rate, using the mid-range of each interval as a robust single-number descriptor, the mean was 24.6 L/s with an inter-regional CV of 25.1%. These findings indicate moderate heterogeneity in temperature and higher variability in discharge, consistent with lithological and structural controls discussed in this section. This statistical summary is intended as a robustness check and does not alter the previously reported ranges.

For the practical modeling of coolant circulation in the heating system, a circuit with a Viessmann Vitotrans 353 heat exchange station was deployed. The tests were conducted with a coolant supply temperature of 55 to 75 °C and a flow rate of 18–22 m³/h. During the operation, the values of heat output, the temperature gradient at the inlet and outlet of the heat exchanger, as well as the gas flow rate used for additional heating in control modes, were monitored. The average heat output of the unit was 330 kW at a minimum supply temperature and reached 395 kW at a coolant temperature of 75 °C (Table 2). As a result of the tests, it was possible to confirm the calculated data on heat exchange efficiency, as well as to establish the efficiency of the system, which, depending on the operating mode, varied in the range of 0.79–0.84.

Table 2 Results of Heat Exchange Station Tests under Different Conditions.

Supply temperature, °C	Coolant flow rate, m ³ /h	Heating capacity, kW	Unit efficiency
55	18.2	330	0.79
60	19.5	355	0.81
65	20.8	375	0.82
70	21.4	387	0.83
75	22.0	395	0.84

Particular attention was paid to measuring the corrosion activity of geothermal waters in relation to the elements of the circulation system and heat exchange equipment. For these purposes, an experiment was conducted with the exposure of steel pipe samples on the KorTest 2200 stand for 72 hours at a temperature of 60 °C. After the tests, the weight loss of the metal and the visual condition of the surface made it possible to assess the corrosion effect. According to the results of the experiment, the average corrosion wear rate was 0.07 mm/year, which does not exceed the maximum standards for low-carbon steels under comparable operating conditions. In

addition, an analysis of the mineralogical composition of the water and determination of the concentrations of the main elements were conducted. The average calcium content was 97 mg/l, magnesium was 26 mg/l, and sodium was 550 mg/l, with a total mineralization of 3.4–8.2 g/l. With higher mineralization recorded in individual wells of up to 15 g/l, an increase in the specific heat transfer resistance was observed within 6–9% compared to less mineralized samples. These data allowed for subsequent modeling to consider correction factors when calculating thermal efficiency (Table 3).

Table 3 The Chemical Composition of Geothermal Water by Main Components.

Index	Central	Western	Southern	Eastern	Northern
Calcium, mg/L	92	105	87	95	118
Magnesium, mg/L	24	31	19	26	34
Sodium, mg/L	520	610	440	570	650
Potassium, mg/L	14	17	12	15	19
Chlorides, mg/L	1800	2400	1600	2000	2600
Sulfates, mg/L	410	560	330	490	620

An important stage of the work was the creation of a three-dimensional digital model of temperature distribution in a section to a depth

of 5,000 meters. Using the Geoligix Discovery and ArcGIS Pro software package, temperature isosurfaces and heat flow density maps were

formed. Alongside the temperature isosurfaces, model uncertainty was mapped (kriging variance) to flag the areas where additional borehole data would most efficiently reduce prediction error. Only zones classified as low to medium uncertainty were used to aggregate thermal potential figures. According to the calculation results, in the most promising areas, the predicted values of thermal potential were 350–480 GJ/km², while in less heated areas this figure was lower, at about 120–180 GJ/km². A series of tests was performed in laboratory conditions to simulate the heat supply of greenhouses with an area of 100 and 500 m² using geothermal water as a coolant. For a greenhouse of a smaller volume with an average coolant flow rate of 5.8 m³/h, the air temperature in the working volume was maintained at 18°C with an outside temperature of –4°C. The average consumption of the conventional fuel, equivalent to the used thermal energy, was 3.9 thousand kg of conventional fuel per month. In a greenhouse with an area of 500 m², similar conditions required a heating capacity of 430 thousand kcal/h and a coolant flow rate of up to 27 m³/h. Specific heat losses through enclosing structures were determined experimentally, which was 58 W/m² with a temperature difference of 20 °C. Summarizing the obtained

experimental data, it can be noted that the total predicted thermal energy productivity for the studied areas was about 18.3 million Gcal/year, which is slightly higher than the initial calculations due to taking into account additional well points and clarification of flow rate and temperature data (Fig. 1). The following values of thermal reserves were obtained for individual areas: 6.5 million Gcal/year in the Central region, 8.4 million Gcal/year in the Western, 3.4 million Gcal/year in the Southern. The average wellhead temperature was 57.4 °C, with maximums reaching 83 °C. The estimated life of the fields at the given flow rates was 28–33 years, with a temperature decrease of 10–15 °C by the end of the service life. In comparison with similar projects implemented in the regions of Central Asia and the Caucasus, the obtained values of thermal engineering indicators are generally comparable (Table 4). Therefore, in several regions of eastern Kazakhstan, the average temperatures of the coolant at the wellhead were about 65–75 °C and 55–68 °C in Dagestan, with flow rates of up to 40 l/s. A distinctive feature of the study was the higher mineralization of thermal waters, in some cases exceeding 12 g/l, which required adjustment of the calculation models and the use of special anti-corrosion measures in laboratory tests.

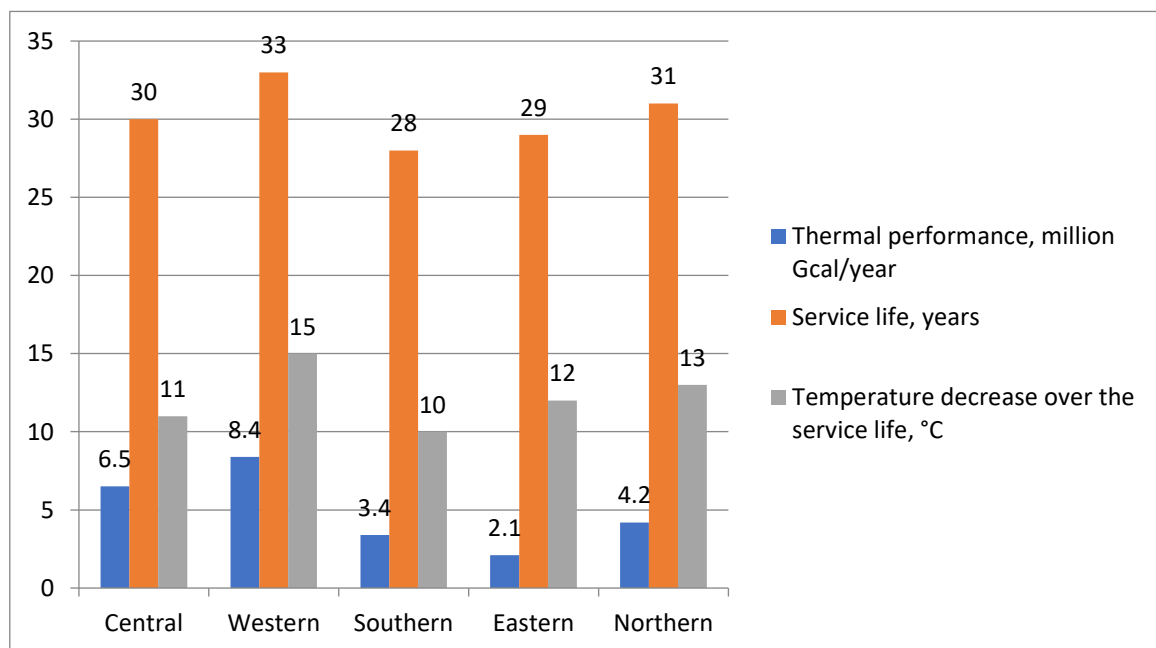


Fig. 1 Forecasted Total Thermal Reserves by Regions.

Table 4 The Comparative Summary of Geothermal Parameters Reported for Analogous Projects in Central Asia and the Caucasus (Indicative Ranges Mentioned in the Text).

Region / Project	Wellhead T (°C)	Flow rate (l/s)	Mineralization (g/l)	Typical use	Source in text
Turkmenistan (this study)	57.4 (avg), up to 83	9–45	~3.4–15 (range across wells)	Greenhouse heating, heat supply	The present study
Eastern Kazakhstan	~65–75	up to 40	n/a	District/greenhouse heating	Text comparison
Dagestan (Caucasus)	~55–68	up to 40	n/a	Heat supply	Text comparison
Uzbekistan & S. Kazakhstan (regional)	~58–72	n/a	n/a	Regional heat supply: 15–17 million Gcal/year total potential	Text comparison

Analysis of the technical and economic efficiency of the exploitation of geothermal resources showed that when replacing organic fuel, the projected annual savings in equivalent fuel could be 2.6–2.8 million tons, which was equivalent to a reduction in CO₂ emissions of 4.1 million tons/year. Additionally, scenarios for the heat exchange station operation with a reduced geothermal coolant supply temperature (up to 45 °C) were simulated in laboratory conditions. In such modes, a 28–34% decrease in heat output was observed, which confirms the importance of operating wells at the maximum temperature of the extracted water. Finally, all experimental data were integrated into the geoinformation modeling system. Based on the results, detailed maps of the temperature field, heat flow density, and well flow rate were compiled for various areas. These maps formed the basis for forecasting the economic potential for implementing geothermal heat supply. The general energy map showed the presence of five large areas with a forecast potential of over 400 GJ/km² and a total combined capacity of up to 2 GW of thermal energy. The results of the study were verified by comparison with published data from similar studies conducted for the regions of Uzbekistan and Southern Kazakhstan, where the total thermal potential, according to recent years, is estimated at 15–17 million Gcal/year at an average coolant temperature of 58–72 °C. The experiments showed that technical solutions for organizing heat exchange and circulation, in most cases, ensured stability of heat output within deviations of no more than 3.5% of the calculated values. The final comparative analysis showed a high degree of correlation between the obtained data and the results of independent experiments and confirmed the reliability and representativeness of the measurements. The obtained results and the created models are a solid basis for developing practical recommendations for the use of geothermal energy in the heat supply of agricultural and industrial facilities, as well as for the subsequent development of eco-technologies in the field of rational nature management.

4. CONCLUSION

The study comprehensively analyzed the thermal energy productivity of Turkmenistan's geothermal resources and confirmed their significant potential for practical use in heat supply systems. Drilling operations using Bauer BG 28H equipment provided representative samples of thermal waters from depths of 600 to 2000 m, which made it possible to reliably determine temperature, chemical, and hydrodynamic parameters. The average water temperature at the wellhead in all areas was 57.4 °C, and the maximum recorded value

reached 83°C, which ensures high efficiency of heat exchange processes. Well flow rates varied from 9 to 45 l/s, depending on the geological structure and depth of the aquifer. Laboratory measurements of heat capacity and thermal conductivity showed that the average heat capacity of thermal waters was 4.18 kJ/(kg K), and thermal conductivity was in the range of 0.59–0.68 W/(m K), which is comparable with similar indicators in the regions of Central Asia and the Caucasus. With the mineralization of above 10 g/l, thermal conductivity decreased by 5–8%, which confirms the need to introduce correction factors into the calculation models. The corrosion activity of geothermal waters, determined based on the results of tests on the KorTest 2200 stand, was 0.07 mm/year, which does not exceed the maximum permissible values and indicates the possibility of their use in steel pipelines, provided that corrosion protection measures are taken. Experiments with the Viessmann Vitotrans 353 heat exchange station demonstrated a heating capacity of 330 to 395 kW, depending on the coolant supply temperature. The efficiency varied within 0.79–0.84, which confirms the high-energy efficiency of the developed heat supply scheme. When modeling the heating of greenhouses with an area of 100 and 500 m², it was possible to achieve stable maintenance of the air temperature at 18 °C with an outside temperature of -4 °C. For a greenhouse with an area of 500 m², a heating capacity of about 430 thousand kcal/h and a coolant flow rate of up to 27 m³/h were required. The three-dimensional digital model of the temperature field distribution to a depth of 5000 m revealed the presence of five promising areas with a predicted thermal potential of more than 400 GJ/km². The total predicted thermal energy productivity for the surveyed areas was about 18.3 million Gcal/year, exceeding the initially expected value due to clarification of the flow rate and temperature data. In particular, the forecast for the Central region was 6.5 million Gcal/year, 8.4 million Gcal/year in the West, and 3.4 million Gcal/year in the South. The estimated service life of the fields under current flow rates and temperature conditions is estimated at 28 to 33 years, with a gradual decrease in temperature by 10–15 °C by the end of the operation. The comparison of the obtained data with similar studies conducted in Uzbekistan and Eastern Kazakhstan showed a high degree of correlation and comparability in thermal characteristics, confirming the reliability of the results. In addition, integrating data into the geographic information system enabled the compilation of detailed maps of the temperature field and well flow rates, which served as the basis for forecasting the economic impact. Hence, the study convincingly demonstrated the significant potential for the

practical application of geothermal resources for heat supply, with the potential to save up to 2.8 million tons of organic fuel annually and reduce CO₂ emissions by 4.1 million tons/year. Implementation barriers and enabling conditions. Near-term deployment in Turkmenistan will be shaped not only by resource quality but also by non-technical constraints: high upfront drilling and surface infrastructure costs relative to regulated heat tariffs; limited standardized permitting pathways for direct-use geothermal and reinjection; and the current scarcity of dedicated policy instruments, e.g., priority access to district-heating networks or targeted incentives. Regional reviews document that legacy energy subsidies and institutional capacity gaps can slow private investment in renewables; conversely, risk-sharing mechanisms for exploration and drilling, tariff reform for heat networks, and clear reinjection/water-use rules would materially improve project bankability and uptake. Future work will focus on optimizing heat-exchange layouts, e.g., secondary-side hydraulics, antifouling regimes, and corrosion control, to reduce exergy losses at lower supply temperatures, and on assessing hybrid configurations that integrate geothermal with solar thermal collectors to enhance seasonal performance. Additional priorities include model updating driven by monitoring (sequential data assimilation) and operational strategies for reinjection and scaling mitigation to extend field longevity.

REFERENCES

- [1] Myradovich PA. **Roadmap for Renewable Energy Development.** *IgMin Research* 2023; **1**(1): 116–121.
- [2] Malozyomov BV, Martyushev NV, Babyr NV, Valuev DV, Boltrushevich AE. **Modelling of Reliability Indicators of a Mining Plant.** *Mathematics* 2024; **12**(18): 2842.
- [3] Rezaei B. **Study of Geothermal Energy Potential as a Green Source of Energy in Iran.** *Geothermal Energy* 2021; **9**(1): 28.
- [4] Zapar WM, Gaeid KS, Mokhlis HB, Al Smadi TA. **Review of the Most Recent Work in Fault Tolerant Control of Power Plants 2018–2022.** *Tikrit Journal of Engineering Sciences* 2023; **30**(2): 103–113.
- [5] Malozyomov BV, Tynchenko VS, Kukartsev VA, Bashmur KA, Panfilova TA. **Investigation of Properties of Laminar Antiferromagnetic Nanostructures.** *CIS Iron and Steel Review* 2024; **27**(1): 84–90.
- [6] Glinscaya A, Tynchenko V, Kukartseva O, Suprun E, Nizameeva A. **Comparative Analysis of Compressed Air Production Equipment.** *E3S Web of Conferences* 2024; **549**: 05009.
- [7] Panfilova T, Tynchenko V, Kukartseva O, Kozlova A, Glinscaya A. **Modernization of Electronic Document Management and Systems Analysis Processes Using an Automated Platform.** *E3S Web of Conferences* 2024; **549**: 09018.
- [8] Kuzkin AY, Zadkov DA, Skeebe VY, Kukartsev VV, Tynchenko YA. **Viscoplastic Properties of Chromium-Nickel Steel in Short-Term Creep. Part 1.** *CIS Iron and Steel Review* 2024; **27**(1): 71–77.
- [9] Al Smadi T, Al-Maitah M. **Artificial Intelligent Technology for Safe Driver Assistance System.** *International Journal of Computer Aided Engineering and Technology* 2020; **13**(1-2): 183–191.
- [10] Penjiyev AM. **Fundamentals of GIS in the Development of Renewable Energy.** LAP LAMBERT Academic Publishing, Germany; 2017.
- [11] Korchmit AV, Drozdov YY. **Casting Quality Enhancement of Bushings Made of Foundry.** *Key Engineering Materials* 2016; **685**: 459–462.
- [12] Akzharkyn I, Yelemessov K, Baskanbayeva D, Konyukhov VY, Oparina TA. **Strengthening Polymer Concrete with Carbon and Basalt Fibres.** *Applied Sciences* 2024; **14**(17): 7567.
- [13] Tynchenko YA, Kukartsev VV, Gladkov AA, Panfilova TA. **Assessment of Technical Water Quality in Mining Based on Machine Learning Methods.** *Sustainable Development of Mountain Territories* 2024; **16**(1): 56–69.
- [14] Penjiyev AM, Penjiyeva DA. **Resources and Efficiency of Geothermal Water Use.** LAP LAMBERT Academic Publishing, Germany; 2015.
- [15] Brigida V, Golik VI, Voitovich EV, Kukartsev VV, Gozbenko VE, Konyukhov VY, Oparina TA. **Technogenic Reservoirs Resources of Mine Methane When Implementing the Circular Waste Management Concept.** *Resources* 2024; **13**(2): 33.
- [16] Taussi M, Borghi W, Gliaschera M, Renzulli A. **Defining the Shallow Geothermal Heat-Exchange Potential for a Lower Fluvial Plain of the Central Apennines: The Metauro Valley (Marche Region, Italy).** *Energies* 2021; **14**(3): 768.
- [17] Previati A, Crosta GB. **Regional-Scale Assessment of the Thermal Potential in a Shallow Alluvial Aquifer System in the Po Plain**

- (Northern Italy).** *Geothermics* 2021; **90**: 101999.
- [18] Mordensky SP, Simmons SF, Ingebritsen SE, Mella M, Crone AJ, Glen JM, Siler DL, Peacock JR, DeAngelo J, Lindsey CR. **Favorability Mapping for Hydrothermal Power Resource Exploration in the U.S. Great Basin.** *Geothermics* 2025; **117**: 102900.
- [19] Huang K, Raymond J, Parmenter R, Grasby SE, Kivi I, Ferguson G. **Canada's Geothermal Energy Update in 2023.** *Energies* 2024; **17**(8): 1807.