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# Risks and economic expediency of using geothermal resources as a source of renewable energy

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**Abstract**
The permanent increase in energy demand on the global level is accompanied by a number of challenges, the main of which is to find new ways and approaches that can level the dependence on limited hydrocarbon resources and promote decarbonization processes in society. In the context of intensive diffusion processes between economic, environmental, and social problems, the most rational option is the transition to renewable energy sources (RES). One of the most promising trends is the development of the geothermal sector, given its inexhaustibility, cost-effectiveness, and lack of direct dependence on seasonal fluctuations.
As part of the study, information on current energy-renewable trends was analyzed and summarized; the current state of the energy system in Ukraine and its prospects under conditions of the geothermal sector' active development were highlighted; the global regulatory sectoral differences were traced and the ways of leveling the existing contrasts with the national system were suggested; the conceptual models were created regarding the most significant risks and threats to the implementation of geothermal projects in Ukraine; the current economic indicators of geothermal facilities in three different promising regions of Ukraine were assessed and the level of feasibility of implementing operations at each of them was determined.
The results of economic assessments proved the perspectiveness of all studied objects. However, in order to minimize the risks of implementing these projects within the period of martial law, recommendations were made on the priority of further operations at each of them.

**Keywords**
renewable energy sources, geothermal resources, normative regulation, heat-energy groundwater, conceptual risk model, economic indicators' assessment, ESG factor

## Introduction

The annual increase in the demand for heat and energy resources at the global level is a major incentive for the ceaseless work of the geological and energy services (ESCO (DOE, 2024)). Their main goal is the search and exploration of new deposits, as well as finding new ways and approaches that would allow us to ensure the full energy supply of the planetary population. Over the years, the only approach to solve this problem was the use of fossil fuels, but their depletion has searched for an alternative more urgent. Consequently, developing areas related to such energy sources as solar and wind have received significant promotion. However, as it has been practically proven, the level of their reliability is variable. The situation in Bangladesh can be considered exemplary in the case where the efficiency of wind power plants is acceptably high only for one-third of the year. Such indicators result from a direct dependence on the wind plant's geographical location and climatic features (seasonal wind fluctuations) (Das et al., 2023). It is precisely this instability that makes it necessary to think about more active involvement in other environmentally safe and stable energy sources. The topic is relevant not only because of the limited availability of hydrocarbon resources but also because the delay in decarbonization causes more and more damage to the environment every year in terms of climate change trends worsening (Harvey et al., 2021). The latter reflects in the gradual deterioration of all its components (soil, groundwater, surface water, and air) and thus poses a risk to human health.

*Statement of the problem and its connection with important practical tasks*. The years of erroneous beliefs about the limitless and universality of fossil fuels, which have been used to ensure the functioning of the global energy system, have consistently brought humanity to the critical point where change is the only option to avoid global collapse. The ongoing depletion of traditional energy resources and inert public reactions to it has become a catalyst for intensive diffusion processes between economic, environmental, and social problems. The increasing competition dynamics between countries for limited fossil fuel resources, along with the growing negative impact on the environment, which in turn affects the living conditions of the population, increasingly questions the effectiveness of the existing system and requires its urgent reorientation. First and foremost, such transformation should be accompanied by strengthening the level of energy and economic security so that not only are energy prices stabilized, but also the politicization of their supply is eliminated, and the risks to the population's welfare are significantly reduced.

Today's most promising solution for updating and rebooting the studied energy sector is the widespread transition to renewable energy sources (RES), paying equal attention to all possible options that currently exist (Kucheriava I., 2020). Despite the fact that the initial stages of implementing a strategy of using periodic or sustainable energy flows that are distributed in the natural environment and have the ability to self-recover require significant structural changes in the innovator-countries' economic systems as well as urgent technological shifts, a significant increase in energy efficiency in the long-term prospect transforms these inconveniences into temporary side effects that can be considered insignificant.

## Analysis of recent research

*Energy-renewable trends (advantages, peculiarities of development and distribution)*. Over the past decade, there have been significant shifts in the field of renewable energy sources and the final formation of an extensive system of industrial trends that may replace their outdated versions in the future. The list of new research objects that appeared in the focus of the energy market includes geothermal, bio-, and hydro-energy, as well as the already mentioned wind and solar ones (Renewables 2022; Kuznietsov M., 2022). And if the technological progress and activities related to the last two points have already reached a significant level in the world, the rate of work in the field of thermal waters is still in a state of development.

The unconditional *advantage of working with our planet's geothermal resource* is its inexhaustibility in the first place (Sukhodolia O., 2013). Even considering the gradual intensification and increasing rates of work in this area over the past few years, the minimal percentage (less than 1%) of its actual use is very indicative. In addition, geothermal energy production can be considered a somewhat economic activity, as it does not require the alienation of large areas (on average 400 $m^2$), and the technological process requires water consumption 50 times less than a standard thermal power plant or nuclear power plant (NASU, 2020). Production of such type of energy is not dependent directly on seasonal fluctuations (seasons and other variable environmental conditions), as well as on the situation with global energy prices. According to statistics, if the studied resource's potential is considered in terms of heat production only, its cost is consistently kept at a level half as high as the cost typical for conditions when natural gas is burned.

Overall, the experience of some countries (Iceland, USA, Italy, etc.) (Paliichuk U., 2012), which have been implementing the necessary steps to reorient the energy system and introducing technologies aimed at providing the population with heat and electricity using the studied alternative energy source for some time, has shown that even under not very favorable conditions (geological, geochemical, temperature, etc.), it is possible to find options for using thermal waters of different quality. For example, if the water temperature is:

- 20 – 30 °C – it can be used in conjunction with heat pumps in frames of the agro-cultural complex development (livestock, aquaculture industry (fish farming), seed heating, etc.);
- 30 – 50 °C – is an indicator of the possibility to connect these waters to underfloor heating systems. Also, it allows the use of thermal resources within panel systems, in frames of centralized heat supply organization, as well as for the arrangement of balneological locations;
- 50 – 70 °C – means that the resource can be used in water desalination, pasteurization of milk, and providing process heat;
- if the temperature range of waters extracted from the subsurface is 70-120 °C, it makes it possible to use them in pulp and paper production;
- more than 120 °C makes it possible to dry wood material.
- And speaking of efficient electricity generation, the temperature of the extracted geothermal resource should be more than 100°C (Abate et al., 2014; Dolinskyi A., 2016)

This, together with the convincing actual results of assessing the efficiency of the implemented reforms in relation to the existing processes in the studied sector, gives reason to consider the gradual reorientation of the energy system as an important factor in the socio-economic transformation. Changing the order that has been established over the decades is seen as a necessary impetus that can significantly contribute to stabilizing the indicators of the global economic system, which is particularly important in the context of the geopolitical instability of recent years. An important argument under these circumstances is the relative unpretentiousness of the geothermal energy extraction process, as it does not require any additional fossil resources for its functioning. The latter is an indicator of the propensity of such systems to minimize the excessive dependence at least partially on minerals or fuels, and can be interpreted as another step towards achieving energy independence. Another reason to focus on the development of geothermal renewable resources is its potential ability to ensure the stability of the country's entire energy system (in the framework of this study, the focus is primarily directed to the situation in Ukraine). Rejecting the traditional approaches to energy supply and focusing only on renewable energy sources, it should be considered that "green" energy sources (sun, wind) are discontinuous, highly variable, and frequently create energy gaps that need to be compensated somehow. Considering that the volumes of geothermal energy production can be adjusted to match the existing demand, the maintenance of the integrity and certain flexibility of the power system will not require too much effort.

Apart from the above-mentioned, the analysis of the practical experience of several countries regarding the implementation of renewable energy policies has revealed other aspects that can positively contribute to economic development and countries' competitiveness growth. In particular, this is manifested through the possibility of creating hundreds of thousands of workplaces (as of 2021, 196,2 thousand employees were involved in the field of geothermal energy, the number of which, according to experts, could reach 28 million people worldwide by 2050) (Energy & Environment, www.statista.com). Such prospects are very relevant, especially for areas with high levels of unemployment. The leveling of this indicator can be achieved by opening numerous laboratories and modern research centers, the main goal of which would be providing studies of the latest approaches to clean energy production by the creation of new infrastructure sectors with modern manufacturing facilities that require workforce and by the opening of new specialties in higher education institutions needed to educate a new generation of professionals who will have the knowledge to promote the chosen clean strategy in the future.

The focus on geothermal resources is also reasonable, considering the prospects of their use through the prism of environmental and economic aspects. Against the backdrop of permanent problems related to climate change, environmental pollution caused by the extraction and processing of fossil energy resources, as well as significant financial losses that follow attempts to mitigate the consequences of all mentioned above, the possibility of changing approaches to those that will be accompanied by challenges of a smaller scale seems to be the best solution.

According to the global scientific community, despite certain difficulties regarding the initial cost being too high, geothermal resources are potentially the cheapest sources of electricity. Its cost is steadily decreasing every year due to the development of technologies, the reduction of their price, and the absence of primary finite raw materials. The list of advantages is supplemented by the absence of high operating costs and the significant reduction of utility costs, which makes the implementation of geothermal projects very attractive, even in the long term. At the same time, the use of thermal fluids is a fairly environmentally friendly process compared to the hydrocarbon resources' extraction, as the operating process of geothermal plants envisages the reduction of greenhouse gas emissions (regulated by the international list of requirements aimed at active prevention of further climate change) and does not imply significant noise pollution (Veselko A., 2015). In this way, a favorable environment is created with the gradual minimization of risks to human health today, as well as the necessary basis for ensuring a decent and safe future for the next generations.

In aggregate, all mentioned above forms a strong basis for argumentation in favor of the expediency of geothermal energy ideas' active promotion at the highest legislative and industrial levels, as well as encouraging the broad population to accept new concepts of ensuring their well-being by shifting the focus of attention to new opportunities.

It should be noted that at the current stage of global development, the rejection and ignoring of existing opportunities offered by the latest "green" energy approach contrast noticeably with the plans declared in the international arena aimed at decarbonizing the existing system and preserving the planet. We can already trace a correlation between the marketing success of any company or initiative and the level of seriousness of their work on the transition of production to an environmentally friendly track. Awareness of this fact often serves as a powerful motivating factor and significantly stimulates active energy reorientation efforts in both individual business units and countries in general.

Current trend analysis of switching to geothermal resources in the process of changing energy strategies has shown a rather low percentage of large-scale projects based on the use of this type of renewable energy source. According to a joint study by Bloomberg New Energy Finance (BNEF) and Frankfurt School-UNEP (Frankfurt School-UNEP Centre/BNEF, 2019), despite the significant perspectives of using the earth's interior energy, the preference is still given to obtaining energy from wind and solar sources as more affordable ones. Thus, tracing the dynamics of global investment processes in geothermal energy (Fig. 1), an obvious conclusion could be drawn about the growing reluctance to develop the financially risky area in the context of global crises (Covid-19 pandemic, the war in Ukraine and Israel) of the recent years.

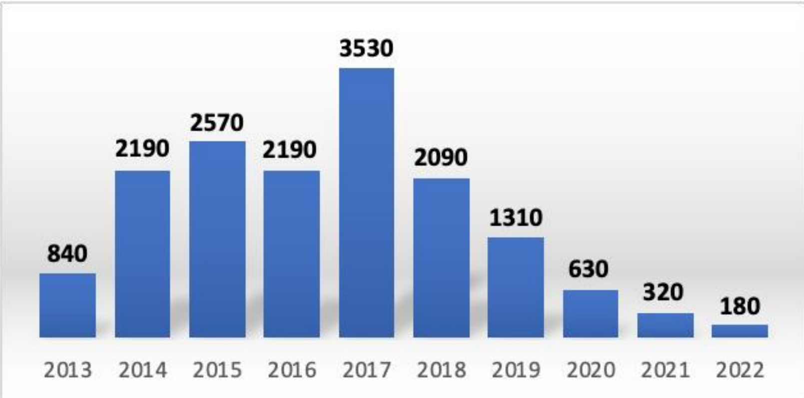


***Figure 1.*** *Global investments in geothermal energy, USD million*

Besides the financial nuances, it is impossible not to notice the changes that have taken place over the past decade regarding the spread of geothermal operations due to the active promotion of development trends in energy renewable energy.

The search for ways to increase electricity availability has prompted the world to monitor carefully and evaluate the potential of each type of renewable energy source. According to the results obtained, geothermal power indicators (Fig. 2) are significantly higher than those of other renewable energy sources. In practice, this was accompanied by a very gradual but gaining momentum of direct geothermal energy production (Fig. 3).

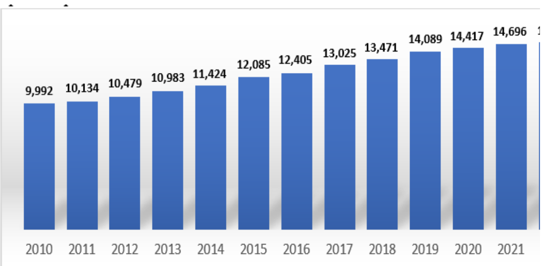


***Figure 2.*** *Global installed geothermal capacity, MW (www.statista.com, www.irena.org)*

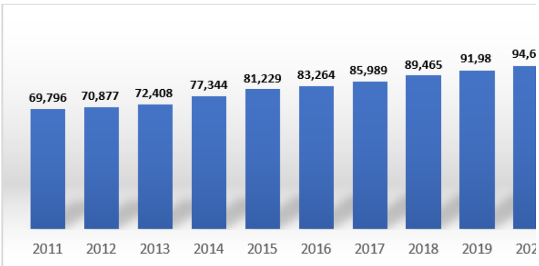


***Figure 3.*** *Globally established geothermal electricity production trend, GWh (www.irena.org)*

At the moment, active steps aimed at expanding geothermal energy and heat production capacities are mainly concentrated in only a few countries. Some other ones are making efforts to maintain at least existing levels. The reasons for such unevenness regarding the studied type of renewable energy source are:

- competitiveness and economic growth rates of countries;
- geographical restrictions on the geothermal systems' distribution that are effective for use (areas of volcanic activity, extent along tectonic plate boundaries) (Park et al., 2021);
- countries' level of technical development and/or low knowledge of national geothermal potential.

During 2016-2021, Turkey, Indonesia, and the United States of America were recognized as leaders regarding working operations with geothermal energy. These are three countries that, even under not very favorable global conditions, have achieved some success in increasing their capacities, adding 0.9, 0.7, and 0.2 GW to their previous indicators (Fig. 4). The success of these countries over the specified period is largely conditioned by correctly selected and implemented strategies regarding extraction of geothermal resources, as well as by high-quality normative regulation. In particular, the increased activity of the Turkish market can be explained by the creation of a few relatively small, and therefore easier to operate, geothermal plants (25 MW or less), as well as by the introduction of a feed-in tariff (FIT) (special tariff for technology), which significantly facilitated the implementation of many projects (Renewables, 2022).

Indonesia's achievement, in its turn, is closely connected with the practice of a wide network deployment of small-sized facilities as a complement to several really large ones (for example, the 45-megawatt Sorik Marapi Unit 2), as well as with the beginning of direct governmental funding of narrowly targeted exploration drilling, which is intended to reduce exploration risks and, accordingly, investment thresholds, since the early stages of geothermal-prospective facilities mastering are exactly those which are accompanied by the highest risks.

Other countries that keep leading positions in the geothermal industry, though not the top ones, are Iceland, the Philippines, Japan, New Zealand, and Italy (Kudria S., 2012). The "clean" energy production field has been developing in these countries in recent years without noticeable jumps (Fig. 5) at a relatively steady speed. Maintaining the existing production volumes, thorough calculation of possible risks, and cautious implementation of new rules and requirements for producers allow to maintain a certain balance when capacity expansion is fixed (less than 0.1 GW in each country), but there is no strong imbalance in the market system (Bertani R., 2015). This is especially evident in the case of New Zealand. The usage of geothermal capacities in this country began with the activities of small-scale facilities and long-term monitoring of fluctuations regarding industrial and commercial electricity demand. In turn, the construction and commissioning of larger-scale facilities (2016, 2023) began only recently, when the system was recognized as ready to increase the amount of energy it receives.

Japan's experience is somewhat different, and on the contrary, it originates from the construction of larger facilities, the inconvenience of which was re-evaluated after the Fukushima accident. Recent practice has shown that a more convenient approach for the gradual development of geothermal energy in the country is to create small plants with a capacity of less than 7.5 MW, which does not require an environmental impact assessment and can be built about twice as fast. These conclusions were followed by immediate regulatory changes, which were reflected in simplifying the project approval procedure and establishing a new feed-in tariff (FIT) for small geothermal plants, which is more than one and a half times higher than for large facilities.

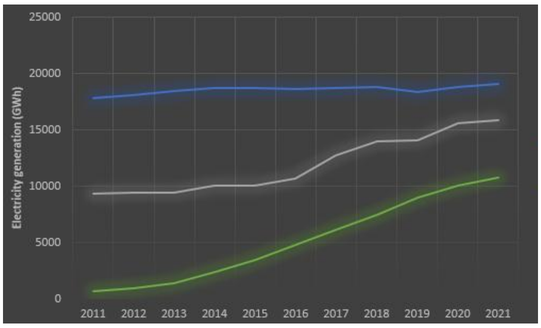


***Figure 4.*** *Geothermal electricity production in the top-leading countries, GWh*

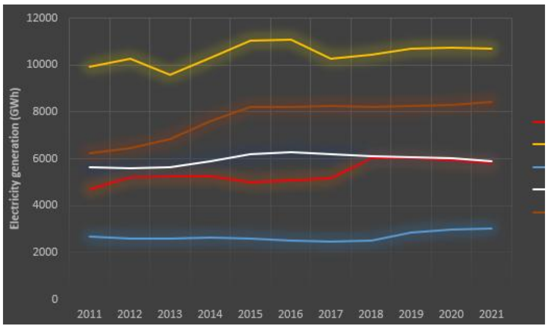


***Figure 5.*** *Geothermal electricity production in leading countries GWh*

***(****made on the basis of the data collected on the www.statista.com**)***

The positive experience of the leading countries in the field of study, together with the described approaches aimed at expanding geothermal capacities, give reason to consider the prospects for further development of this type of energy to be encouraging, albeit not fast. To a large extent, the above-mentioned examples of the spread of the renewable energy sources of the studied type concern countries from different parts of the world, which differ significantly in physical and geographical conditions and levels of economic and technical indicators. This brightly illustrates the impossibility of establishing a monopoly regarding operations with geothermal resources, which is a definite plus against the current politicization of regulatory processes regarding their traditional fossil analogs.

It is also worth highlighting that the main argument that conflicts with the economic feasibility of geothermal projects' implementation (at least at their initial stages) is the price, which will not have the same weight over time as it does now. This is largely because, as a result of improved technology, the cost of the electricity-generating process from geothermal sources has fallen significantly over the past ten years. In the future, due to the gaining of new experience by developers, the scale of implementation, and the constantly growing competitiveness of suppliers, this trend will only grow.

*The current state of the energy system in Ukraine and its prospects under conditions of the geothermal sector' active development.* The analysis of the native energy system's ability to self-sufficiency with primary fuel and energy resources makes it obvious that there is an urgent need to modify and improve the existing system (Diachuk O., 2017). Even before the full-scale war started, Ukraine was one of the energy-deficit countries and was able to satisfy only a third of its needs (excluding energy from nuclear power plants). And the deployment of military operations on the state's territory only made the situation much more complicated.

Due to enemy actions, the entire energy system was affected. In particular, a number of mines focused on fuel minerals extraction were flooded, and their recovery seems very unlikely in the future. Nineteen power units of thermal power plants were damaged, four units more were stopped, and eight units of hydro-generating stations were damaged. The current situation has also impacted significantly that part of the energy sector, within which planned capacities were provided with the help of renewable sources. Due to the predominant (3/4) concentration of facilities connected with the renewable sector in the southern regions (Kherson and Zaporizhzhya), which were partially and temporarily occupied, about 75% of wind energy capacities and more than 20% related to solar generation were stopped or destroyed. The consequences of the war did not spare the gas transportation system either. At the moment, it is getting significant damage in cities where active battles continue and which are objects for rocket attacks, not to mention the fact that the seizure of the Zaporizhzhia Nuclear Plant, which provided 40% of Ukraine's total nuclear power, did not contribute to the establishment of energy stability.

Considering all of the above mentioned, one of Ukraine's priorities, for the moment and for the near future, is the intensive restoration and development of the energy system. The important thing here is the rejection of traditionalism, which is expressed by the efforts to make oil and gas production the only basis of energy independence. Using a wider range of energy generation opportunities, smoothly reorienting existing approaches to the "green" ones according to the European Green Deal is now not only desirable for Ukraine, as a candidate country for joining the EU, but also sufficiently promising for leveling the destructive consequences of war at an accelerated pace.

Determining the state's energy system form of existence in the long term is already relevant today, as conceptual planning must be based on the actual capabilities estimated for each region of the country, which will be united in the future. Under the current circumstances, the revision of the attitude towards the geothermal potential of Ukraine can play a significant role.

According to the predictive assessment made by the Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine, three areas are considered the most promising with the technically accessible energy potential of geothermal waters (Fig. 6) (Paliichuk U., 2012; Morozov Yu., 2017):

- Western Ukrainian area - includes parts of Volyn, Ternopil, Chernivtsi regions and almost the entire territories of Lviv, Ivano-Frankivsk and Transcarpathian regions;
- Southern Crimea area (including Kherson and Odesa regions);
- the Dnipro-Donetsk Basin area, which covers the territory of Chernihiv, Sumy, Poltava, and Kharkiv regions.

Geological studies have established that the annual potential of the explored geothermal waters in Ukraine is 27 million $m^3$/day with an average temperature of 70°C. In total, this energy resource is equal to 12 million tons of equivalent fuel, which, according to the Institute of Renewable Energy of the National Academy of Sciences of Ukraine, may allow annual savings of about 10,5 billion $m^3$ of natural gas (this is approximately 40% of Ukraine's annual consumption (according to 2021 data)) (Dolinskyi A., 2016).

A strong argument for increasing the scale of involvement of this renewable source type is also the multi-vector nature of directly related areas, within which additional energy resources can significantly affect the socio-economic level of regional development. Thus, for example, the involvement of geothermal water deposits explored in previous decades and, first of all, using already existing wells on these deposits could significantly affect Ukraine's energy complex. At the time, a significant percentage of these wells stopped their work since geothermal circulation systems there were built using equipment that was intended only for the period of exploration geological work, and the subsequent replacement of equipment to the one which would meet the requirements of long-term operation did not take place. Considering the above-mentioned price reduction for the necessary technologies, re-equipment of these facilities today is quite real and expedient. Especially considering the fact that this will make it possible to create modern functioning heat generation facilities with a total capacity of 200 MW (140 MW of which could be received by using capacities of existing wells), thereby providing heat to a large number of human houses and significantly saving the amount of traditional fuel and energy resources.


***Figure 6**. Regions of Ukraine that are promising for geothermal energy development.*

Another option is the realization of geothermal prospects in locations where active exploration and industrial development of underground hydrocarbon raw material reserves are held. Geothermal resources of Ukraine are often represented by thermal waters and heated satellite waters, which are brought to the surface by active wells within oil and gas fields. Their predominant concentration in rocks with reservoir properties and limitations by overlapping rock complexes with low values of specific heat conductivity only confirms the existing connection with hydrocarbon accumulation centers (Orlov O., 2010). This, as well as the analyzed foreign experience (Hungary), gives grounds to consider the hypothesis that there is a wider range of opportunities within oil and gas areas and that, in the near future, it would be possible to combine both types of energy resource extraction strategically.

It should be noted that the existing oil and gas areas developed infrastructure of business entities, concentration in their frames of significant qualified human, technical, and technological resources, as well as an equipped network of wells of various types and purposes - in total create conditions under which the presence identification and extraction of geothermal resource can be carried out according to a significantly simplified algorithm. Under the above-mentioned conditions, there is no longer any need for preliminary geological exploration and additional drilling of industrial wells, and therefore, there is no need for significant capital expenditures. Accordingly, the possibility of obtaining a double profit in two different segments at the same time is quite real, and moreover, it is a good incentive to intensify activities along this vector.

The third promising area related to the use of Ukrainian geothermal resources is also at the intersection of several sectors at the same time - energy, medical, and economic ones.

The geological exploration data obtained in the 60s of the last century confirm not only the energy potential of the Western Ukrainian and Southern Crimean regions but also the promising prospects for the use of local geothermal waters for medical purposes (Barylo A., 2019). Many springs identified within these regions are unique, with no analogs in many respects (especially in terms of balneology). But despite this, the level of popularization of the use of these resources is currently unreasonably low. Moreover, the percentage of facilities actively used for medical and recreational purposes does not increase since the major number of wells remains plugged (e.g., in the Arabatska Strilka area, Henichka area).

Given the current war-crisis causal chain, the maximum possible realization of all regional capacities is an obvious chance for the country's rapid recovery in the future. The case of the southern and western regions is interesting because of the possibility of combined realization of the geothermal resource in several directions simultaneously. Thus, within individual municipalities, it is possible to:

- ensure the required level of energy generation (under conditions of decentralized approach implementation);
- arrangement of specialized medical facilities;
- increase the number of tourists.

In total, this will be accompanied by the optimization of existing infrastructure and the creation of a new one, as well as by an increase in social and economic welfare. Furthermore, the successful realization of such projects will serve as an illustrative example of the efficiency of modern green technologies implementation and will simplify the process of attracting investments in similar projects in the future.

Accordingly, the turn to geothermal energy is a good opportunity for Ukraine to make a qualitative leap in improving its economic indicators.

*Highlighting unresolved parts of the overall problem.* An important nuance in the process of geothermal projects' implementation in Ukraine is the need for a complex approach based not only on the geological data obtained in the last century (albeit of high quality) but also on the changes in current economic trends, normative regulation, and existing risks. Currently, it is of high importance to systematize the set of known industry features gathered from the worldwide practical experience, which includes:

- analysis of the best geothermal resource processing methods;
- identification of key difficulties within the operational process with heat-energy waters and possible ways to solve them.

Moreover, there is a need to evaluate foreign and native regulatory features of the industry to find the most efficient and painless diffusion path that could be used in the process of Ukraine's European integration. This will allow further modification of the existing system to a more transparent one, thereby expanding the possibilities of extraction and realization of the studied resource. In this way, the real needs for project support will acquire qualitative contours and justification, increasing the value of these projects in the eyes of investors.

*Formulation of article goals*. This study is based on the results of monitoring both regulatory and practical challenges that pose barriers to the development of the geothermal sector in Ukraine. The main goals are:

- tracking global regulatory sectoral differences and providing proposals regarding the leveling of existing contrasts with the national system of Ukraine;
- creating conceptual models of the most significant risks and threats to the geothermal projects' implementation in Ukraine and the ways of minimizing them;
- assessing the economic indicators of geothermal facilities located in various promising regions of Ukraine, considering current realities, and providing recommendations on the priority of further operations within each of them.

## Presentation of the main material

It was statistically established that the best economic indicators in the framework of dealing with geothermal resources are provided through the active use of heterogeneous steam-water mixtures and natural steam (Shydlovskyi A., 2007). Around a quarter of a hundred countries worldwide are expanding their capabilities to use it and improving their ability to qualitatively equip specialized facilities intended for the industrial conversion of this resource into a subject of further sale (into the energy).

The most efficient supply of energy from this type of renewable source is facilitated by the operation of geothermal power plants and geo-power plants, the capacities of which are rationally distributed among various public or business entities. The operation of these facilities is accompanied by compliance with certain methodical approaches, each of which is selected individually, depending on the situation in which the work is planned.

Thus, in the case of creating a geopower plant, the actual temperature of the water extracted from the subsurface plays an important role. The most convenient for use are those with a temperature of 107°C and higher (www.cosvig.it). Lower temperatures allow electricity generation but require the involvement of other, more complex operating schemes or additional heating using local energy sources (coal, gas). Implementing such options is possible, but in such cases, supporting projects with high-quality feasibility studies and environmental impact assessments becomes even more important. Primarily, this is due to the need to identify not only the economic but also the environmental feasibility of projects in a timely manner, highlighting existing uncertainties and gaps in business plans.

The environmental uncertainties are tied to the fact that the parallel use of fossil energy resources can negate the declared environmental friendliness of the project, affecting the level of social trust towards such initiatives. In the future, this can have consequences during public discussions dedicated to the start of new projects and increases the risk of new approaches' rejection, thus creating obstacles to the sustainable use of geothermal energy. A timely assessment of the economic side of the issue is critical for determining the rationality of the planned actions, considering the additional costs of technological upgrades and the involvement of the above-mentioned additional resources. An important nuance is the differentiation of situational models and the rejection of attempts to use the method of analogies all over. After all, in some cases, the use of additional technologies or energy resources to work with low-enthalpy sources may be more promising financially than working with greater depths to extract high-temperature water with its pure steam.

At this stage of development, a specific list of geothermal resource processing methods has become widespread in the world, particularly in Europe. The most actively used approaches include three schemes:

- The *direct scheme* is the most developed sectoral technology that involves the use of dry geothermal steam (DiPippo R., 2012). The essence of the method is quite simple and involves directing steam to a steam turbine that generates electricity. A positive aspect is the possibility of applying the scheme both in cases of working with high-temperature sources (Iceland) and with sources where the heat carrier is steam of relatively low enthalpy (California, Italy, Indonesia). At the same time, installing an additional liquid-vapor separator is unnecessary, which reduces the likelihood of technical malfunctions and ensures high operational reliability and efficiency.

- The *indirect scheme* involves a more complex process based on the use of geothermal fluid. The approach envisages water supply to a pressurized evaporator, where evaporation occurs after the pressure is discharged, and then the steam is sent to the turbine. Depending on site-specific characteristics, there can be one (Single Flash) or two (Double Flash) stages of water separation. The installation of additional circuits for water and steam purification from aggressive compounds and gases could be required as a function of the geological and hydrogeological site characteristics.
- A *closed binary scheme* is successfully implemented in practice due to the interaction of hot water with a liquid in the second circuit, which acts as a working fluid with a lower boiling point (Anderson A., 2019; Dolinskyi A., 2016). Both liquids pass through a heat exchanger, where hot thermal water evaporates the low-boiling working fluid, the vapor of which is sent to the turbine. The use of working fluid with a relatively low boiling point allows the use of not-very-hot thermal waters as a primary energy source.

In conditions where, due to the reasons mentioned earlier, it is not possible to carry out extraction operations from really high depths, it is rational to focus on low-enthalpy geothermal resources. A significant advantage of the last ones is that they are potentially available without significant geographical, territorial, and climatic restrictions and are usually located at shallow depths. These waters are characterized by temperatures sufficient to ensure the functioning of almost two dozen different activities related to heat supply, agriculture, balneology, and industry.

Difficulties in these cases are associated with the problem of unification of technological systems and equipment of geothermal power plants due to the wide variation of individual characteristics (mineralization, hardness, pH, gas composition, level of gas saturation) of each reservoir. Despite this and the fact that high-quality heat supply through geothermal circulation systems is only possible if they are strictly linked to the location of the geothermal power plant, it is consistently confirmed by various feasibility studies that it is advisable to expand the network of such plants gradually. For these reasons, the world has been actively developing methods to intensify the extraction of thermal waters, as well as means of concentrating and transferring the heat flow to the places of application. These methods could be distinguished as:

- intensive technologies have been developed whereby wastewater with a high level of mineralization is injected back into the underground reservoirs;
- an intensive method of development supported by thermal pressure and accompanied by the creation of zones of increased penetration is being introduced;
- there is ongoing work on the development of the technology aimed at using the energy of dry, hot rocks, which includes drilling parallel wells, creating cracks between them (by fracturing), passing cold water through the formed system, and producing steam or a steam-water mixture from which heat is released.

All the approaches and methods described above greatly simplify the development of deposits with geothermal potential. Accordingly, they significantly impact increasing the rate of resource use, including low-enthalpy ones, thereby contributing to the achievement of the global sustainable development goals set out in the 2030 Agenda. Naturally, this process is not uncontrolled. To maintain safety guarantees, numerous guidelines, regulations, and laws restrict all operations with geothermal resources, the main purpose of which is to minimize potential risks associated with possible negative environmental impacts. Thus, ensuring a rationally balanced movement is important to achieve "a significant increase of the renewable energy share in frames of the global energy balance" and "doubling the global rate of energy efficiency improvement".

At the same time, the high strategic potential of geothermal resources declared in the UN 2030 Agenda (UN, 2019) was not accompanied by concrete specifications regarding work with them. The document gave an understanding of the prospects but did not provide a clear understanding of how their classification should be treated and how the projects should be managed. According to practical experience, the lack of specifics on such issues does not contribute to the acceleration of the diffusion of geothermal opportunities into the modern energy system. Moreover, the lack of clear, simple, and reliable technical rules regarding

- how to identify the discovered resource,
- where does it make sense to implement solutions regarding their realization (without negative consequences for the environment),
- how to plan the development of such projects,

It creates serious uncertainty for the business, as developing the energy sector under such conditions is too risky. The need for a common platform for transparent assessment and comparison of the potential of renewable and non-renewable energy portfolios has been growing year by year, becoming more and more critical. To a certain extent, this was caused by the expansion of the circle of stakeholders (in addition to manufacturers-players within the energy market, interest in the issue was expressed by investors-regulators, governments, and consumers), who needed a common system for assessing and comparing different types of energy sources, using it as a basis for a comprehensive overview of current and future energy sustainability scenarios at different levels (project, company, region, country or the world as a whole). This is important because the 17 global sustainable development goals are closely interconnected in such a way that changes in one area have an unconditional impact on the achievements in others. Under the described conditions, the desired socio-economic-ecological balance can be significantly infracted due to a violation of ensuring sufficient, reliable, affordable, and ecologically responsible energy supplies. For these reasons, at the end of 2022, globally agreed geothermal standards (additional regulatory specifications regarding the Resource Classification Framework use) (UN Framework Classification, 2022) were approved at the UN level, focusing exclusively on energy resources of the relevant type and aimed to cover existing gaps in system functioning. This document has created a fundamental, global basis for use in the geothermal sector. However, making real adjustments to the current state of affairs, within which the system of rules in the studied segment became increasingly confusing over the years, is not a matter of one day. Besides, the existing significant diversity in approaches to geothermal energy, with significant differences between countries and, on a smaller scale, regions, does not simplify the situation.

Even before the new specifications came into effect in 2020, an in-depth methodological study of scientific, technical, and regulatory documents regarding the use of geothermal energy in many countries was conducted (De Giorgio et al., 2020). Considering the implementation of a new regulatory document (new specifications) that is relevant for all UN member states, as well as a more detailed review of new documents implemented in Ukraine and amendments to the old ones, the developed map (2020) of regulatory documents within the research area at the national and international levels has been changed (Fig. 7).

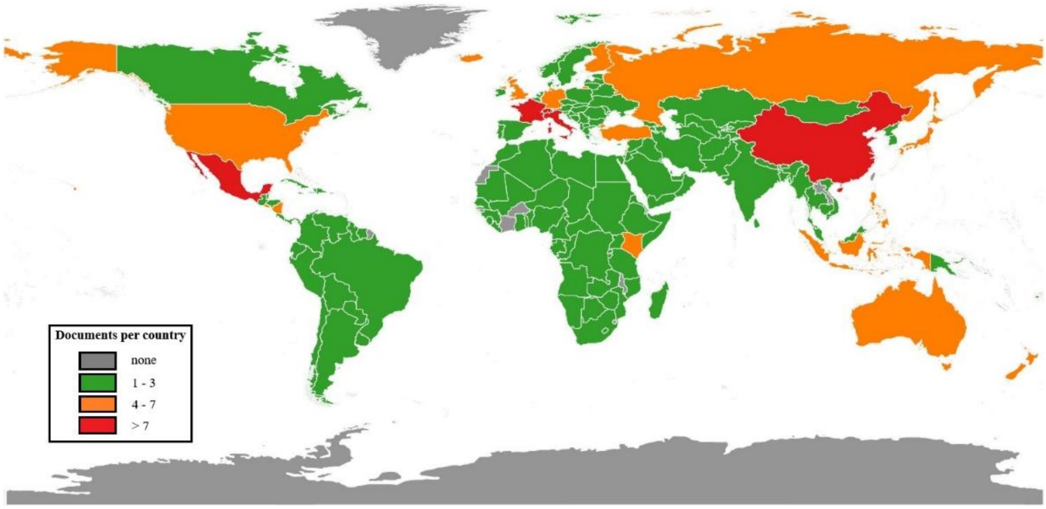


***Figure 7.*** *National occurrence map of selected documents and continental percentage. National (or sub-national) and international (more than one country involved) documents were considered.*

It should be noted that the rules that regulate the development and realization of geothermal resources are usually defined in the context of legal regimes related to water resource use. The issue of normative support was studied by analyzing both the experience of countries that have been working on this sector development for a long time (Italy, Netherlands, Austria, Switzerland, Germany) and the country that is just starting active work in this direction (Ukraine).

Monitoring the legislative background (Muffler, P., 1978) gives grounds for considering the structure of most sectoral documents in these countries to be heterogeneous and fragmented in terms of application. In the case of the EU, such a level of insufficient elaboration is primarily represented by the absence of common legislation (for instance, relevant sectoral Directives) on a number of issues related to work at geothermal facilities, as well as by the complexity of solving this problem. The latter is because many European countries simply do not have special legislation to regulate work with the studied resource. Another frequent problem (common to both Europe and Ukraine) is the lack of specifics in the provisions of existing documents. The main disadvantage is their totally declarative nature regarding the support of the spreading of the practice of geothermal resource use. This situation is unacceptable in the context of modern transformation processes aimed at improving the level of environmental protection. Considering the fact that national normative acts in Europe generally regulate geothermal resources from this perspective, the situation requires careful monitoring and adjustments.

The lack of effective national regulation in some European countries has also led to the development of chaotic processes within the geothermal sector. The requirements of the simultaneous orientation to international regulations, which have significant differences, and national documents of different ranks (guidelines, regional laws, etc.) developed at the regional level and at the same time referring to provincial level acts unbalance the existing system, significantly complicating the research and development process. Existing regulatory approaches in European countries were fully described in the research results of 2020 (De Giorgio et al., 2020), but to clarify the prime causes of barriers' appearance in the way of geothermal sector development. Table 1 presents the key theses, which are followed by a number of countries that are recognized as leaders in the field in Europe today.

*Table 1 Guidelines for the geothermal sector management in European countries*

| | |
|---|---|
| Germany | ✓ No unitary federal system.<br>✓ The existence of a requirement to obtain a concession from the water authorities of the relevant region for the construction of geothermal plants (low-enthalpy ones). |
| Netherlands | ✓ Operations with geothermal systems are regulated by the relevant water legislation (e.g., the Water Act).<br>✓ The existence of requirement to obtain special permits for extraction and realization of geothermal resources from local authorities. |
| Austria | ✓ All forms of use of low-enthalpy geothermal resources are regulated by the Federal Water Law.<br>✓ Dealing with geothermal resources is restricted by the largest number of prohibitions in Europe.<br>✓ Geothermal legislation contains the largest number of prohibitions aimed to protect artesian and multilayer aquifers. |
| Switzerland | ✓ The procedures of permit's approval for the construction of geothermal plants are regulated by the national legislation on water protection.<br>✓ Detailed rules for working with geothermal facilities can be established by each autonomous canton separately, depending on the territorial features. |
| France | ✓ The use of geothermal low-enthalpy resources is carried out per the national standard, which is based on a system of thematic national maps highlighting three types of zones (green, orange, and red).<br>o Each zone requires the observation of a different set of rules regarding the extraction of low-enthalpy geothermal resources.<br>o Obtaining a permit for future work within the green and orange zones requires the submission of a personal application by the applicant.<br>o Obtaining a permit for future work within the red zone requires the submission of a personal application together with a documentary certification of competence from a professional expert.<br>o A mandatory requirement for the geothermal plants' construction within the red zone is to obtain a positive conclusion from the preliminary environmental impact assessment.<br>✓ The description of current restrictions regarding operations with geothermal resources is a part of the existing mapping system. |
| Italy | ✓ Research and development of geothermal resources are regulated on the basis of a unique national licensing provision in frames of the old, but still valid, legislation that provides the combination of geothermal energy obtaining together with other mineral resources.<br>✓ Regional governments have full authority to manage geothermal resources.<br>✓ The functioning of different geothermal schemes requires adherence to different procedural requirements.<br>✓ There is a very wide range of small but significant differences in referential or legislative sources, in the way of functioning of different competent institutions, and in authorization procedures at the regional and provincial levels.<br>✓ No unified regulatory base for regional or sub-regional (provincial) rules. |

It follows from all the foregoing that, at the moment, the most common ways of regulating the geothermal sector in European countries are the general framework and the local one. The undoubted advantage of the last one is the possibility of its fast achievement. However, as it was proved in practice, it is also often accompanied by:

- numerous delays, ineffective regulation, or its absence;
- creating difficulties for subsurface users;
- and low public awareness of the benefits of using geothermal resources.

On the other hand, general framework ways may be accompanied by significant losses in case of insufficiently high quality of regulation, but the concept of such an approach itself is accompanied by a number of positive aspects, including:

- the existence of detailed guidelines for individual non-governmental institutions aimed for their further use depending on the existing geological features (for instance, in Switzerland and France);

- promotion of the introduction to the use of uniform definitions and systemic procedures;
- improvement of the local regulatory base by taking technical and environmental aspects into account.

Analyzing the geothermal experience of foreign countries is an important element in energy transformation planning in countries where, until recently, the sector has not received sufficient attention to implement large-scale changes. This also refers to Ukraine. However, it is worth mentioning that the regulatory foundation for ensuring the protection of groundwater resources, some of which are heat-energy ones, was laid in Ukrainian legislation back in 2007, long before the signing of the EU Association Agreement, the relevant provisions of which require changes in existing approaches regarding climate and energy issues. The Instructions approved by order of the State Commission of Ukraine on Mineral Resources No. 182 are still relevant today as well, having integrated the concept of "heat-energy groundwater" into the list of geothermal energy sources (SCMR, 2007). However, the described by the document:

- regulatory peculiarities of providing geological exploration regarding heat-energy groundwater;
- requirements for the level of deposits' study, as well as for the calculations regarding operational reserves and for resource evaluation of mentioned waters;
- nuances of heat-energy groundwater fields' readiness for industrial development;
- and operational reserves' use conditions.

do not differentiate different types of geothermal sources.

The current document does not make a difference between subgeothermal (with low enthalpy), hydrothermal, and petrothermal waters. This is an obvious gap since the wide variation of natural conditions in different parts of Ukraine's geothermally perspective regions, as well as the variations regarding the sources' characteristics, urgently requires methodological guidelines for assessing conditions with different geothermal potential. This is necessary for improving operational accuracy and for preliminary planning of ways in which the work with defined geothermal sources will be provided. This requires the existence of not only a developed technological base but also a normative one that would fully ensure the legitimacy of the respective resource's extraction.

In recent years, Ukrainian legislation has been supplemented by several laws (on alternative energy sources, the electricity market, combined heat and power production, heat supply, etc.) that, to some extent, relate to aspects associated with geothermal energy and the regulation of its use. A number of new versions of some old documents (for instance, the Subsurface Code and the Tax Code) were adopted with appropriate amendments. Unfortunately, within these documents, the direct connection to the studied area is often very indirect and fragmentary. The approval of guidelines and articles in frames of laws that are so general to be applicable to all (or most) non-conventional and renewable energy sources at once is a common phenomenon. In other words, the specifics of geothermal energy and its production mechanisms are not sufficiently reflected in the documents, leaving many gaps and controversial issues. For example, uncertainty regarding the classification of geothermal groundwater, double rent, etc., could be mentioned.

However, some of the implemented details (such as regulation of the "green" tariff charged for electricity produced from geothermal energy by generating facilities; peculiarities of tax exemption regarding operations on import of equipment which runs on renewable energy sources or is necessary for the production of the latter, etc.) are gradually forming a legislation network of anchor points that can be used for future regulations and development plan realization, pursuing the reduction of barriers for geothermal energy development (Diadkovych V., 2021). This gives grounds to believe that, despite the current crisis and the pause (2021-2023) regarding activities related to operations at the relevant facilities, the next National Plan until 2030 will include a description of clear steps to solve the identified problems as well as proposals for specific technologies that would be promising for increasing the flexibility of Ukraine's integrated energy system.

Among previously highlighted most common regulatory options, the obvious way to accelerate the Ukrainian geothermal development is to adopt a local framework approach. Considering internal state peculiarities and the need to launch a sectoral mechanism based on maximum transparency and environmental friendliness, the time advantage of this approach will not be able to ensure the required level of efficiency. According to this research, the most rational solution at the current stage of the country's development is to draft a unified framework with detailed guidelines regarding both operations with high-temperature waters from great depths and low-enthalpy resources. In this way, favorable conditions will be created for users, who will have clear explanations of existing opportunities, as well as their rights and obligations in frames of the project's implementation, regardless of the spatial location and temperature conditions of geothermal facilities.

The suggested approach differs from the one practiced at the level of European legislation. The latter mainly focuses on regulating the nuances of working with geothermal sources with exclusively low enthalpy. This is because most countries have no favorable conditions (tectonic, geological, hydrogeological, etc.) to extract and realize high-temperature waters from very big depths efficiently. However, such a restriction seems irrational from a long-term perspective, considering the constant technological upgrades that are becoming more and more extensive every year. Considering this, as well as Ukraine's progressive geopolitical rapprochement with Europe, it would be a logical step to combine the two situational models. The outcome of such actions will be drafting a full-fledged shared legislative framework based on agreed common recommendations regarding the geothermal plants' operation and the classification of risks associated with the active exploitation of various types of geothermal resources. Thus, agreeing on a single common document will be happening not only in Ukraine's integration into the European system but also in the leveling of gaps in the latter, which will significantly simplify partnership work and make the project space accessible to a wider range of investors.

*Risks of geothermal projects' implementation in Ukraine.* Having critically assessed the situation with geothermal extraction in Ukraine, it became clear that there are two key risks that are the most problematic for its more active financing: environmental risks and risks of the project's credit attractiveness. Both are complex and cover a wide range of issues. Their combined negative impacts do not give confidence in the feasibility of modern progressive projects' implementation, thus significantly slowing the transformation of Ukraine's energy sector.

At the current stage, entrepreneurs often face a dilemma, as the declared "aspiration to a clean and positive impact" intended to demonstrate a qualitative contribution to a sustainable future is confronted with the strongly marked economic unattractiveness of operating in the geothermal sector, especially in the short-term perspective. The current tendency to prioritize non-financial indicators somewhat mitigates the situation for investors but still does not eliminate the urgent need to develop new strategies (Maury et al., 2022) that could minimize the negative effects caused by various reasons.

In order to specify the main challenges associated with the mentioned categories of risks, the existing and potential problems in the sector were ranked by urgency. The results reflected in the following conceptual models (Figs. 8, 10) are obtained through a detailed analysis of the experience of native geothermal facilities' functioning and the specifics of prospective areas for implementing new advanced projects in the future.

The mentioned conceptual model risks are not the only ones, but the key ones. The hazard of indicated *environmental risks* is primarily connected with difficulties regarding making predictions of the actual event development during the operation of a geothermal facility, especially in the context of deep and extra-deep drilling.

In case of an incorrect approach regarding heat-energy water extraction and its further processing, all environmental elements become the objects of exposure. First of all, their changes are reflected in a sharp violation of the ecological balance (for instance, disturbance of natural ecosystems) and deterioration of public health (for instance, due to the contamination of drinking water) (Fig. 8). Such infringement of the human right to a healthy environment does not contribute to the popularization of projects in this area and requires thorough preliminary planning of their management in the safest way.

A real threat to the implementation of geothermal projects in Ukraine is also the propensity to develop dangerous exogenous geological processes within the above-mentioned perspective areas. The most frequently recorded phenomena are landslides, karst, and subsidence. The intensity of their manifestation varies. For example, landslide activity is the highest within the western Ukrainian region, the eastern parts of the Dnipro-Donetsk Depression, and the western part of the Southern Crimean area. In its turn, subsidence is more often recorded specifically within the Dnipro-Donetsk depression and in the eastern parts of the western Ukrainian region, while in the south, this phenomenon is hardly ever observed. Karst processes are also naturally occurring on the eastern edges of the western Ukrainian region (mainly in Ternopil, Ivano-Frankivsk, and Lviv regions), as well as in the south of the country but in limited quantities and, according to historical statistics, very rarely in the northeast (Dnipro-Donetsk Depression). The predisposition of territories to the mentioned processes' development is caused by many factors (Chen et al., 2020), mainly their geological, hydrogeological, and climatic conditions. Geothermal resource extraction significantly intensifies the processes, disrupting the stability of soils and rocks, thereby increasing their instability. The latter should be taken into account in order to avoid accidents in Ukraine, such as those that occurred due to geothermal activities in Leyte, Philippines (March 1, 2013) (www.rappler.com), where a large landslide occurred, or in Kamojang, Jawa Barat Province, Indonesia (2006-2007), where a 6 cm subsidence occurred (Zaenudin, Kadir, Santoso, Abdassah, & Kamah, 2010).

Another potential hazard that is most often associated with heat-energy resource extraction from great depths is its gas accompaniment (Gaysina L., 2015). In case of insufficient study and lack of necessary precautions, a potentially environmentally friendly and profitable project can end up with a large-scale accident caused by hydrogen release to the surface (Lohne H.P., 2019) (Fig. 8). Such possibility should be considered in the process of business plans' drafting in frames of which possible scenarios are considered. Accordingly, the projects should be accompanied by necessary countermeasures that would help to avoid such force majeure and minimize the existing risk.

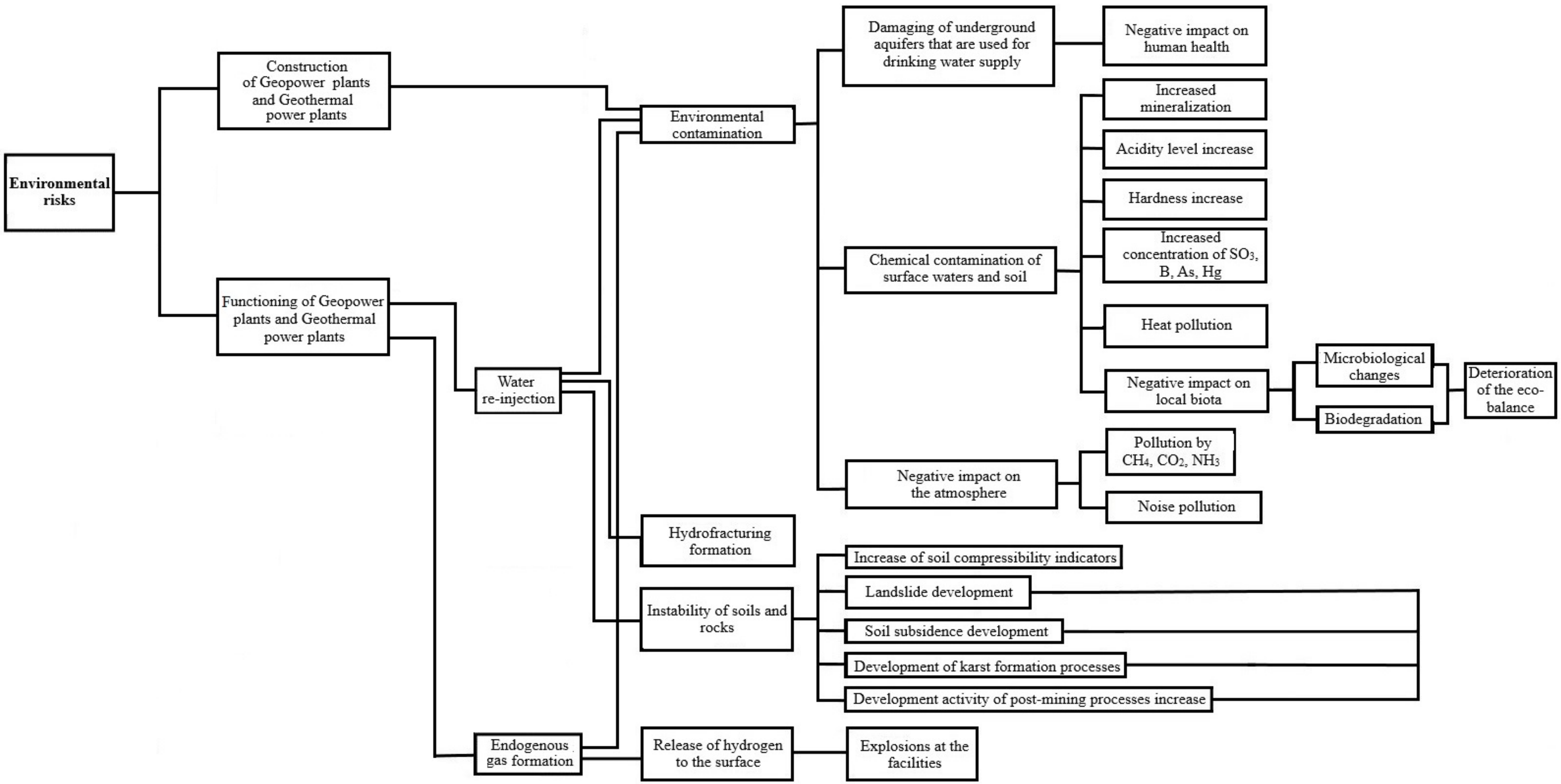


***Figure 8.*** *Conceptual model of environmental risks that accompany the geothermal projects' implementation.*

In analyzing the environmental challenges related to the realization of geothermal operations in Ukraine, a special decision tree was developed (Fig. 9), which reflects proposals aimed at minimizing the probability of natural and technogenic imbalanced development. The approach is considered rational as it allows maneuvering, choosing the best ways to maintain the state of the environment depending on the specific conditions of each project, and forming a holistic approach to environmental and social governance (ESG).

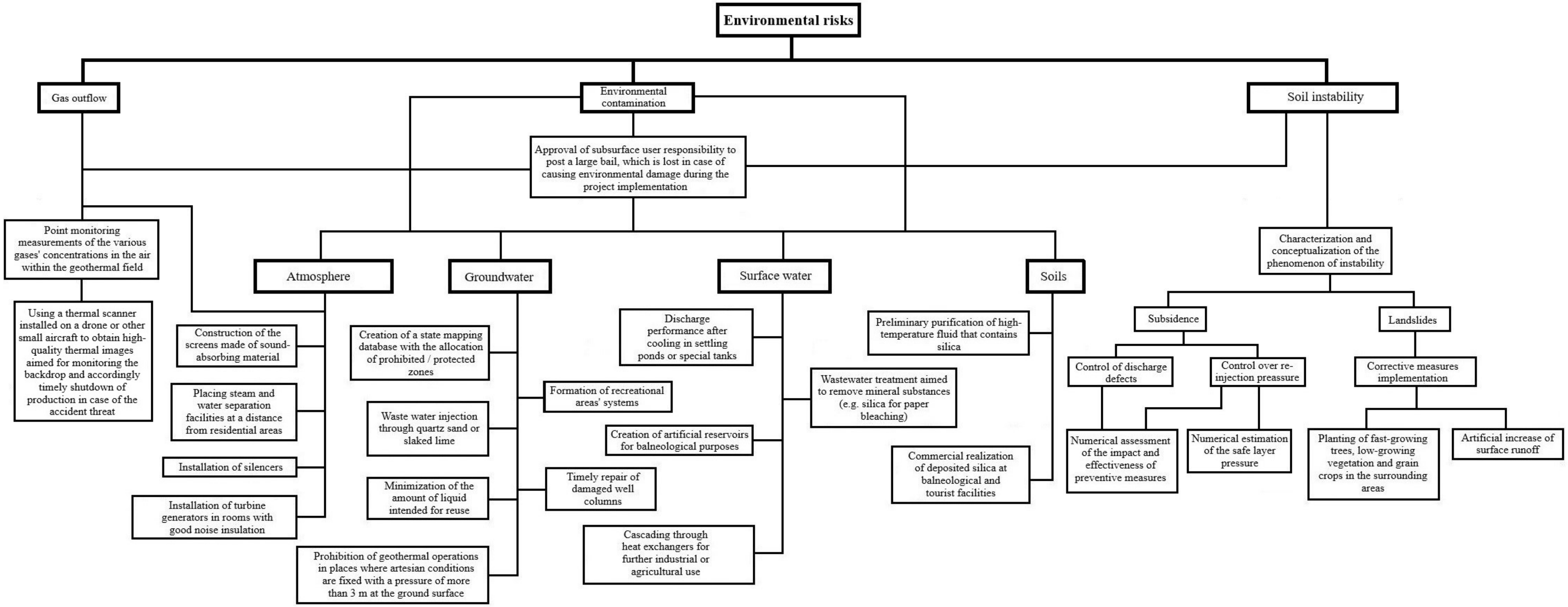


***Figure 9****. Decision tree regarding environmental risks*

Apart from the mentioned ESG factors, the decision on the perspectiveness of the idea regarding extraction and use of heat-energy resources in a particular region is significantly influenced by the level of the project's credit attractiveness (Fig. 10).

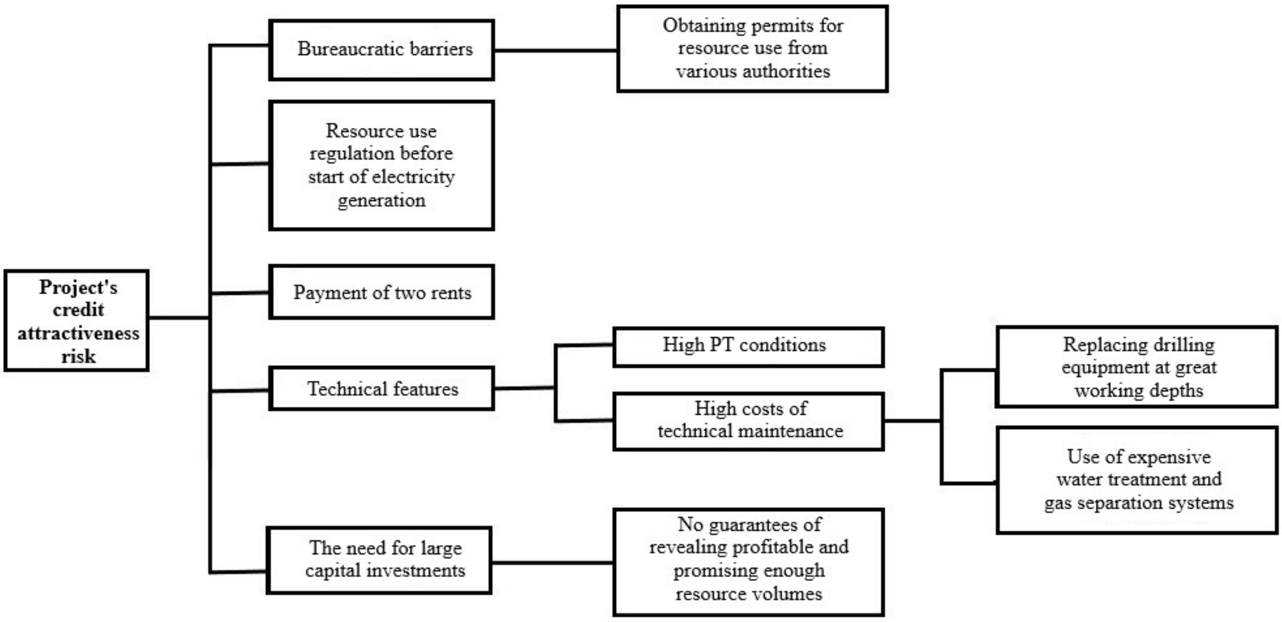


***Figure 10.*** *Conceptual model of project' credit attractiveness risk*

Unfortunately, Ukrainian subsurface users often face the inability to ensure the last one. This is greatly facilitated by the previously mentioned gaps in legislation and the complex specifics of geothermal extraction's technical features, which is accompanied by the need for large-scale investments. The possible ways to mitigate and, to some extent, level the impact of these obstacles on geothermal energy development are presented in Figure 11. However, the only way for companies to guarantee the financial and economic sufficiency of projects is to be flexible regarding implementing new strategies and approaches. In particular, it concerns:

- the ability to respond quickly and effectively to changes in shareholders' expectations (due to a number of industry challenges);
- the ability to find optimal mutually beneficial compromise solutions during consultations;
- achieving results that meet the stated intentions;
- building trusting relationships with communities by guaranteeing and fulfilling commitments regarding minimizing the negative impact of mining activities on their habitats, environment, and heritage sites.

Together, this contributes to strengthening the company's brand position and credibility, increasing the possibility of access to capital (project financing, granting of loans aimed to ensure sustainable, environmentally friendly development) due to a good reputation. The latter is due to the fact that in the context of an active global prompting towards decarbonization, it becomes more common that the investor's favor is given to responsible companies with a high ESG rating and practically proven desire to contribute to the sustainable future of the country by reorienting to work with renewable energy sources (Corporate Social Responsibility Law, 2016). In this context, if the geothermal sector is included in the list of priorities at the state level, accompanied by an appropriate legislative framework, the implementation of projects will become much more affordable.

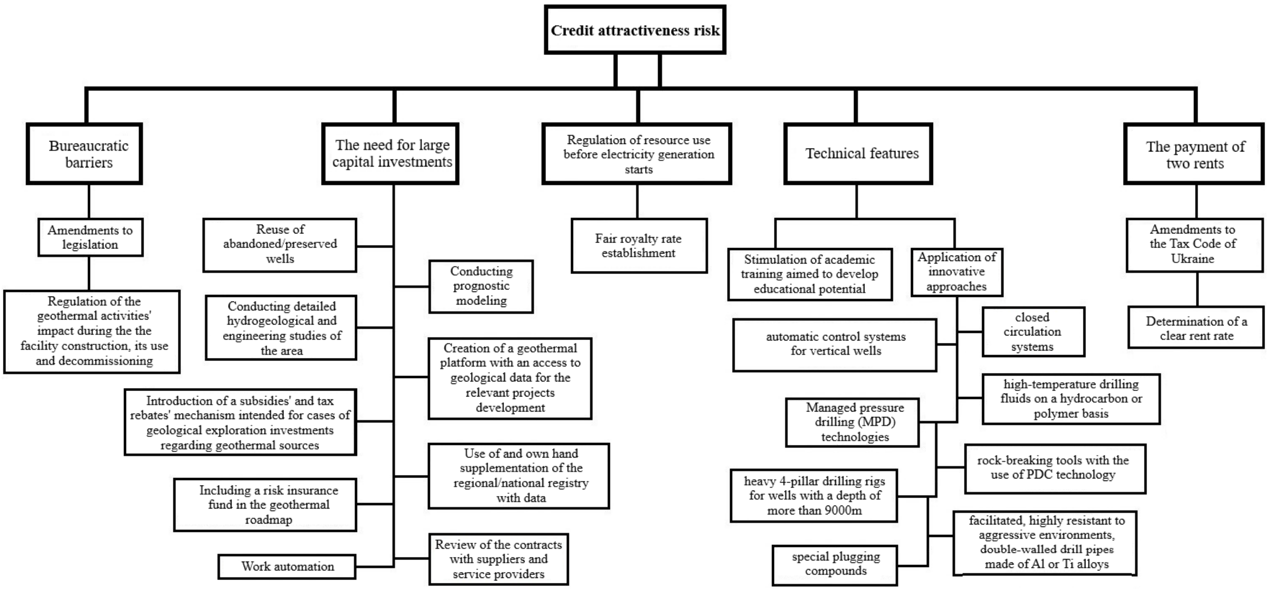


***Figure 11**. Decision tree regarding credit attractiveness of the project*

*Assessing the economic indicators of Ukrainian geothermal facilities taking into account current realities.* The options concerning the practical use of the Ukrainian subsurface's geothermal potential were actively explored at the end of the last century. Due to the growing popularity of the idea, its development was accompanied (back in Soviet times) by significant financial support, which allowed it to provide a successful feasibility study of numerous facilities in different regions of the country. The consequent development of projects aimed at using geothermal plants for heat supply assumed the use of rationally based plans. However, at the time, the economic situation was an absolute and unconditional barrier regarding their implementation (for example, the heat tariff set at that time made all these projects totally unprofitable).

Against the backdrop of gradual transformations of economic processes in recent decades that were ongoing before the global crises started (the Covid-19 pandemic, the outbreak of war in more than one country), an attempt to reassess some of these projects was made (Shurchkova Yu., 2020). The study had positive results, but the change in the global environment over the past four years requires considering new trends and relevant arguments to attract the necessary investments (including foreign ones) that are needed to implement the projects.

In order to establish modern (as of the beginning of 2024) prospects regarding the use of the existing potential of geothermal waters to support Ukraine's energy supply in the conditions of war and reorient the system in accordance with the world's decarbonization priority, three different sites were chosen from the previously mentioned geothermal-promising regions of the country:

1) Medvedivka village – Southern Crimea area;
2) Berehove area, Transcarpathian region – Western Ukrainian area;
3) Monastyryshchy village, Chernihiv region – Dnipro-Donetsk Basin area.

Within the framework of the study, all technical solutions (Zharnikova R., 2007) that were reflected in the old versions of the projects were left unchanged. Yet, the calculations were performed considering a significant change in the current tariffs (set in the general context, not for the period of martial law), the income tax rate, and the devaluation processes in accordance with the current discount rate. Considering the instability of Ukraine's national currency and the obvious desirability of involving foreign investors in the launch of geothermal projects, the basic economic indicators of the selected sites were evaluated using data in foreign currency equivalent, considering changes in the refinancing rate set by the European Central Bank over the past decade. For clarity, the results of the re-indexation of capital expenditures and operating expenses for heat production, as well as all subsequent results that were obtained, are presented in euro, dollar, and hryvnia equivalents, according to the current exchange rate (January 2024).

The list of indicators used to analyze the expediency of using the geothermal potential of chosen areas includes:

- annual amount of heat realization (the volume that can be sold to consumers):

$$G = \frac{D}{T} \tag{1}$$

where $D$ – income from the heat sales; $T$ – heat tariff.

- gross profit:

$$P_{gr} = D - Ф \quad (2)$$

where $Ф$ – operating expenses excluding amortization.

- income tax:

$$H = (D - Ф - A) \times C_t \quad (3)$$

where $A$ – amortization charges;
$C_t$ – income tax rate.

- production profit:

$$P_{pr} = D - Ф - H \quad (4)$$

- payback period:

$$t = \frac{K}{P_{pr}} \quad (5)$$

where $K$ – capital expenditures.

- production cost:

$$P_c = \frac{operating\_expenses}{annual\_heat\_sales\_volume} \quad (6)$$

- full self-cost:

$$C = Ф + H + \left(\frac{A}{G}\right) \quad (7)$$

- profitability:

$$P = \frac{income\_from\_the\_heat\_sales}{operating\_expenses} \times 100\% \quad (8)$$

In this way, each of the studied cases was considered in the most complete way, allowing us to assess critically their prospects.

The possibility of geothermal heat supply to Medvedivka village in the Dzhankoy district was proved on a long experimental basis before the annexation of Crimea (Kudria S., 2012). The initiative didn't get a follow-up with the appropriate implementation due to changes in geopolitical circumstances. However, having an awareness of the existing perspectives is an important element of strategic planning for rebuilding the country after restoring its sovereign integrity. Considering this, although the results of the calculations (Table 2) that were conducted regarding the given site will require further updating, they still provide a current understanding of the resumption feasibility of work there.

*Table 2. Project economic indicators of a thermal power plant in Medvedivka village, Crimea.*

| Economic indicators | Medvedivka village, Crimea | | |
|---|---|---|---|
| | unit of measurement | **2012** | **2024** |
| Capital expenditures | UAH | 71139,764 | 249677,26 |
| | $ | 8903,6 | 6537,77 |
| | € | 6745,15 | 5997,95 |
| Operating expenses for heat production | UAH | 42340,608 | 148602,09 |
| | $ | 5299,2 | 3891,13 |
| | € | 4014,55 | 3569,84 |
| Amortization charges | UAH | 21264,51 | 74631,15 |
| | $ | 2661,39 | 1954,21 |
| | € | 2016,20 | 1792,85 |
| Heat tariff | UAH/ MW*h | 54,97 | 2716,56 |
| | $/ MW*h | 6,88 | 71,13 |
| | €/MW*h | 5,21 | 65,26 |
| Income tax rate | % | 21% | 18% |

| | | | |
|---|---|---|---|
| Income from the heat sales | UAH | 159815,98 | 560901,86 |
| | $ | 20002 | 14687,14 |
| | € | 15153,0303 | 13474,44 |
| Annual heat sales volume | MW*h/year | 2907,33 | 206,48 |
| Gross profit | UAH | 138739,88 | 486930,92 |
| | $ | 17364,19 | 12750,22 |
| | € | 13154,69 | 11697,45 |
| Production profit | UAH | 114070,05 | 412716,96 |
| | $ | 14276,60 | 10806,94 |
| | € | 10815,60758 | 9914,622 |
| Payback period | year | 0,62 | 0,60 |
| Profitability | % | 4 | 4 |

Several factors prove this at once:

- *The reduction of capital and operating expenses as well as amortization charges*. The amount of funds required for the full implementation of the project is now significantly lower than in 2012. Two factors have a significant impact on this trend: economic and technological. The first one is related to changes that occur due to economic fluctuations and is reflected in changes in refinancing rates. The technological factor is expressed in the constant development of technological progress, which, over time, is followed by a certain reduction of cost and an increase in availability regarding technologies developed in the past.
- *heat tariff increase*. The constant increase of this indicator over the past decade convincingly actualizes the current need to involve new sources that could stabilize the level of energy resources (slowing down their deficit trend) and, accordingly, heat.
- *reduction of income tax and the full cost of the generated heat* (Fig. 12).

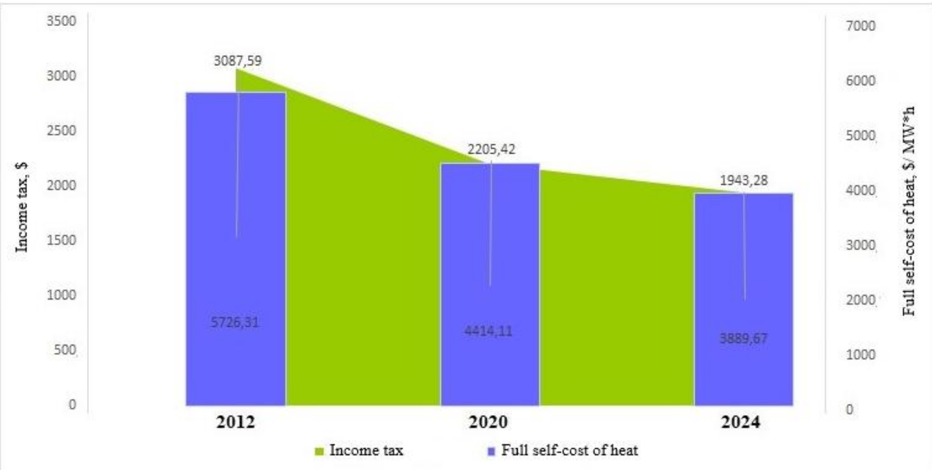


***Figure 12.*** *Changes of key factors of prospectiveness (taxes, self-cost) within the studied object of the Southern Crimea area.*

Under such circumstances, even in case of increasing inflation, which will significantly impact gross and production profits, it will make sense to continue operations at the studied site.

- An additional argument for recognizing the project within the Medvedivka area as potentially successful is the established *profitability index*. Its low value restrains the level of taxes required for payment and is also an argument for obtaining a license to extract heat-energy groundwater at a much lower price. But at the same time, its value is close enough to the European Central Bank's discount rate to provide certain guarantees that the project's financial indicators will be maintained at an acceptable level.
- Moreover, considering the required dynamics of the processes needed to restore the full functioning of all industrial sectors of the Ukrainian peninsula after de-occupation, the predicted *payback period* of such significant projects is of great importance. The obtained result regarding the time required to return the invested

funds has not changed significantly over the past 12 years, and this gives grounds to consider the average payback period of 7 months to be a stable constant, typical for a particular site with specified conditions.

Another object of this study is the Berehove area of the Transcarpathian region, which was identified as a perspective more than 20 years ago (Shurchkova Yu., 2020). To a large extent, this is because it is located in that part of the Western Ukrainian area where the natural climatic and hydrothermal conditions are considered to be the most favorable for operating with geothermal resources. The results of previous hydrogeological studies proved the possibility of extracting heat-energy groundwater from depths of more than 1 km in this part of Ukraine, thus providing industrial inflows sufficient for thermal loads of up to 6 MW.

However, the analysis and updated calculation of the project's economic indicators regarding the study area demonstrated somewhat contradictory results. For a quarter of a century, during which the site was frozen, its characteristics underwent significant changes, directly dependent on global economic fluctuations. Thus, since the idea of putting the Berehove area into operation in 1998 using specially drilled exploration and production wells was conceived, the financial needs for the project's implementation have been steadily increasing and were almost three times higher at the time of the reassessment in 2020. The trend did not develop further, and the required expenditures began to decline gradually, which can be explained by the previously mentioned reasons. At the same time, technological progress has reduced the defined 15 years required for the project's payback to almost half of that time. And yet, the defined low rate of profitability (below the refinancing rate) is a reason to question the feasibility of carrying out operations within this site and using its current heat and energy resources. According to the data presented in the tables (Tables 2-4) regarding the financial requirements for project coverage, it can be concluded that the Transcarpathian region, as a part of the Western Ukrainian geothermal-promising area, requires higher operating costs than those which are needed in other regions despite its confirmed general perspectives. Along with much more complex geological conditions, this gives grounds to consider the decision to postpone operations in this area until the period of active post-war stabilization of the country's economy is quite logical. In the meantime, it is highly recommended that regular monitoring (in a similar way to the one used) of changes regarding the project's indicators be provided in order to define the most favorable circumstances for the project launch.

*Table 3. Project economic indicators of a geothermal heat supply system within the Berehove area, Transcarpathian region, while using specifically drilled exploration and production wells.*

| Economic indicators | **Berehove area, Transcarpathian region (new wells)** | | | |
|---|---|---|---|---|
| | unit of measurement | **1998** | **2020** | **2024** |
| Capital expenditures | UAH | | 117135885,6 | 126665739,72 |
| | $ | 1564736 | 4208979 | 3316725,31 |
| | € | | 3421934,146 | 3042867,26 |
| Operating expenses for heat production | UAH | | 23188011,66 | 25074524,52 |
| | $ | 488268 | 833202 | 656573,04 |
| | € | | 677400 | 602360,59 |
| Amortization charges | UAH | | 5418027,89 | 5858823,67 |
| | $ | 62589 | 194683 | 153412,51 |
| | € | | 158278,86 | 140745,42 |
| Heat tariff | UAH/ MW*h | | 2198,01 | 2716,56 |
| | $/ MW*h | 13,97 | 78,98 | 71,13 |
| | €/MW*h | | 64,21 | 65,26 |
| Income tax rate | % | | 18% | 18% |
| Income from the heat sales | UAH | | 39889546,07 | 43134850,21 |
| | $ | 253528 | 1433329 | 1129480,24 |
| | € | | 1165308,13 | 1036220,4 |
| Annual heat sales volume | MW*h/year | - | 18148,03 | 15878,48 |

| | | | | |
|---|---|---|---|---|
| Gross profit | UAH | - | 22119562,30 | 23919149,37 |
| | $ | | 794810,00 | 626319,70 |
| | € | | 646186,99 | 574605,23 |
| Production profit | UAH | - | 19113286,11 | 20668290,74 |
| | $ | | 686787,14 | 541196,41 |
| | € | | 558363,53 | 496510,46 |
| Payback period | year | > 15 | 6 | 6 |
| Profitability | % | - | 1,72 | 2 |

The last studied location is confined to the Monastyryshchi geothermal field. The site was chosen not solely because of the declared characteristics of the local hot waters (97°C) but rather because of the need to examine the chances of successful use of wells used in the petroleum industry for geothermal purposes. The field's location in the north-western part of the Dnipro-Donetsk Basin (DDB), in frames of which the eastern - one of the largest in Ukraine - oil and gas region is located, makes it possible. Based on the data and results obtained by previous researchers (Shurchkova Yu., 2020), an assessment was conducted to determine the feasibility of activating the processes aimed at restoring the operation of preserved and abandoned wells as of 2024, thus obtaining the understanding regarding the future effectiveness of these wells in case of appropriate investments.

Likewise, in the previously examined objects, the values (Table 4) of feasibility indicators for carrying out activities around Monastyryshchi village have undergone significant changes since the huge volumes of heat and energy resources were discovered here in 2001. The most pronounced change is observed in the income tax rate, which has significantly affected the level of the tax itself, which is mandatory for payment (Figure 13).

*Table 4. Project economic indicators of geothermal heating plants in Monastyryshchi village, Chernihiv region.*

| Economic indicators | **Monastyryshchi village, Chernihiv region** | | | |
|---|---|---|---|---|
| | Unit of measurement | **2001** | **2020** | **2024** |
| Capital expenditures | UAH | | 34798632 | 37629753,65 |
| | $ | 1042000 | 1250400 | 985330,025 |
| | € | | 1016585,366 | 903972,50 |
| Operating expenses for heat production | UAH | | 2333601,16 | 2523456,864 |
| | $ | 55901 | 83852 | 66076,3777 |
| | € | | 68172,36 | 60620,53 |
| Amortization charges | UAH | | 1391945,28 | 1505189,73 |
| | $ | 39752 | 50016 | 39413,1901 |
| | € | | 40663,41 | 36158,89 |
| Heat tariff | UAH/ MW*h | | 2198,01 | 2716,56 |
| | $/ MW*h | 15,91 | 78,98 | 71,13 |
| | €/MW*h | | 64,21 | 65,26 |
| Income tax rate | % | 30% | 18% | 18% |
| Income from the heat sales | UAH | | 16055822,75 | 17362080,21 |
| | $ | 102051 | 576925 | 454623,73 |
| | € | | 469044,72 | 417085,99 |
| Annual heat sales volume | MW*h/year | 6414,27 | 7304,71 | 6391,20 |
| Gross profit | UAH | | 15114166,87 | 16343813,08 |
| | $ | 85902,00 | 543089,00 | 427960,54 |

| | | | | |
|---|---|---|---|---|
| | € | | 441535,77 | 392624,35 |
| Production profit | UAH | | 12644166,98 | 13672860,88 |
| | $ | 72057,00 | 454335,86 | 358022,02 |
| | € | | 369378,75 | 328460,57 |
| Payback period | year | 14,5 | 3 | 3 |
| Profitability | % | 2 | 7 | 7 |

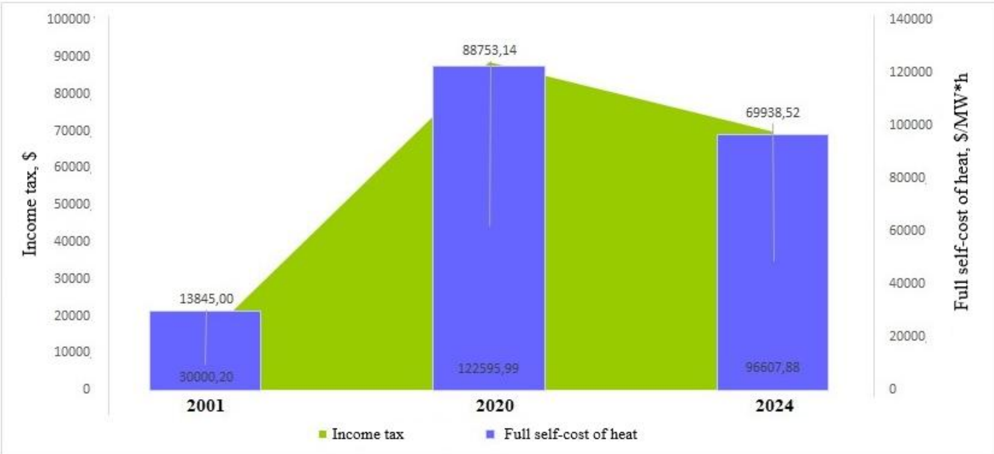


***Figure 13.*** *Changes in key factors of prospectiveness (taxes, self-cost) within the studied object in frames of the Dnipro-Donetsk Basin*

Furthermore, a short payback period in case of operation commencement can be considered a significant project advantage. Its reduction of almost 5 times (compared to 2001) gives grounds to assess the existing prospects as favorable even under the current crisis circumstances and to use this fact as an indisputable argument in the process of obtaining the appropriate financing. In fact, focusing on the obvious upward trend of the profitability indicator, the probability of attracting investor's interest is estimated as high since the obtained values, in this case, are higher than the European Central Bank's refinancing rate but still is not excessive enough to create a threat of unprofitability regarding planned operations due to excessive taxes and license cost.

## Conclusions

The gradual depletion of traditional energy resources and the linear reactions to the problems that follow this trend are cornerstone issues of the present day that require urgent resolution. Focusing on the possibilities of using heat-energy groundwater as one of the sources of renewable energy opens a wide range of opportunities for transforming the existing energy systems of the countries. Ukraine is a typical representative of the latter, with an urgent need to develop new conceptual approaches to energy sector management. The high level of geological exploration of its subsurface simplifies the perspective geothermal area selection process, but the existing risks create difficulties in making accurate predictions regarding the facilities' development. The issue can be partially resolved by ranking these risks in terms of urgency and developing scenarios aimed at leveling or minimizing them as much as possible while also updating project indicators considering current economic and technological trends.

The obtained results regarding the tested objects (according to the described procedure) confirmed their perspectives, but only one of them - Monastyryshchi village, Chernihiv region - is recommended for current practical operations. Its estimated indicators convincingly prove the existence of the entire necessary range of conditions that could ensure project investment security. Meanwhile, the impossibility of guaranteeing this type of security in the case of the sites within the Western Ukrainian area gives grounds to temporarily exclude them from the list of priorities for active operations as of the nearest future (until Ukraine overcomes the crisis). The Crimean site (Medvedivka village) is recommended for further regular monitoring regarding the variations in project economic indicators, updating the data to start operations immediately right after de-occupation if the obtained, in frames of this study, results do not undergo any drastic changes.

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