UDC 621.316.11

A. S. Bondarchuk, Cand. Sc. (Tech.), Assoc. Prof.

Odessa National Polytechnic University, Odessa, Ukraine, e-mail: asb@te.net.ua

UTILIZATION OF WASTE MINE CAVITIES AS RENEWABLE ENERGY ACCUMULATORS

А. С. Бондарчук, канд. техн. наук, доц.

Одеський національний політехнічний університет, м. Одеса, Україна, e-mail: asb@te.net.ua

ВИКОРИСТАННЯ ВІДПРАЦЬОВАНИХ ШАХТНИХ ПОРОЖНИН В ЯКОСТІ АКУМУЛЯТОРА ВІДНОВЛЮВАНОЇ ЕНЕРГІЇ

Purpose. Development of the technology and presentation of the results of calculation of the effectiveness of waste mine cavities utilization for renewable energy accumulation.

Methodology. Simulation of the technology process of receiving, saving and use of solar, wind, and geothermal energy, which uses mine cavities (Odessa catacombs) for accumulation of the energy.

Findings. We have proved the high performance and investment appeal of the technology of the mine cavities utilization as the accumulator of the renewed energy for technological needs for production, hot water supply, heating during the winter period and space cooling during the summer period due to the geothermal energy of stone walls.

Originality. We have presented the innovative technology of use of the abandoned mines (Odessa catacombs) for the accumulation of renewable energy for the needs of the city.

Practical value. We analyzed the available options of use of different types of the renewed energy sources in Odessa region. We evaluated their power, economic, and ecological efficiency and approximated the payback periods of such projects taking into account market conditions. It may give almost unlimited economy of traditional energy resources at the minimum negative influence on the environment.

Keywords: *mine, energy-storage, solar thermal collector, wind turbine, photovoltaic power station, renewable energy, environment*

Introduction. The Energy Strategy of Ukraine provides for the steady buildup of effective use of renewable energy sources of all types. Nowadays, the need for “green growth’” in economic development, which means the fight against the global warming and overcoming the economic crisis, becomes pressing. The technological modernization, improvement of the energy efficiency of the economy, and the introduction of the environmental innovative investment projects are on the agenda [1–3].

Resent research analysis. Ukrainian and foreign scholars have devoted lots of their works to the problems of utilization and accumulation of the energy from renewable sources.

Professor Pivnyak G. G. provides an extensive coverage of the wind power engineering as one of the most promising sources of “clean’” energy in Ukraine [2]. In his monograph, Professor Razumnyi Yu. T. gives guidance on the effective use of electric power and fuel in different spheres [3]. Prakhovnyk A. V. pays lots of his attention to the distributed energy generation in the power supply systems [4]. Professor Denysiuk S. P. introduces the standards of energy efficiency in Ukraine [5]. The European IPPC Bureau suggests different ways of energy resources saving [6].

The unsolved aspects of the problem. However, the technology of economical storage of the energy received from the different renewable sources remains out of view.

Task. Development of the model of the technology process of receiving, saving and use of solar, wind and geothermal energy, which uses mine cavities for accumulation of the energy and allows saving conventional energy sources and diminish the negative impact on the environment.

Results. We made a case study of the utilization of the abandoned building-stone mines (catacombs) in Odessa for accumulative storage of energy received from renewable sources (Fig. 1).

The well-known Odessa catacombs have an overall length of 2.5 thousand kilometers (to compare with Paris catacombs that reach only 300 kilometers and Rome catacombs that reach 500 kilometers). The depth of the catacombs in Odessa varies from several meters to 100 meters.

During previous centuries people have been using the catacombs for different purposes. Nowadays we can use them as a unique accumulator of green energy for the welfare of the city. The temperature inside the mine cavities remains stable over the year and varies from +11 to +14 °C depending on the depth.

The catacombs can be used as an accumulator for the energy in several ways, taking into account their structure and dimensions, and depending on the energy sources combination (Fig. 2).

The first option is to use a mine cavity as an accumulator of heat. The energy from a renewable source, for example, solar thermal collector (STC), is transferred by the heat carrying fluid through the insulated line to a thermal insulated storage reservoir, which is located in a mine cavity and is filled with the fluid (water or special solution) (Fig. 3).

To reduce costs, the reservoir should be built inside the cavity of a required length. The walls should be

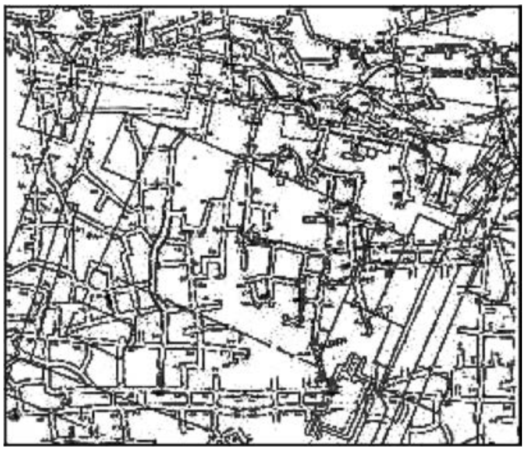

Fig. 1. Location of the abandoned mines (catacombs) under the buildings of the city of Odessa

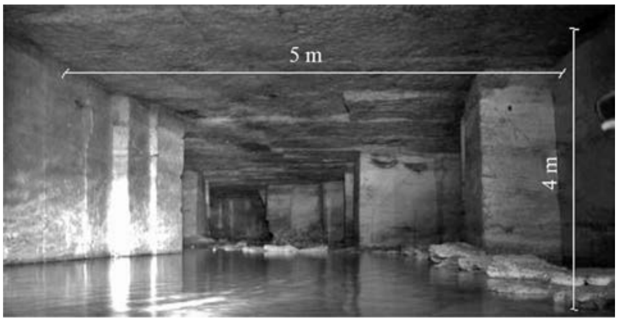

Fig. 2. Abandoned mines in the city of Odessa (catacombs)

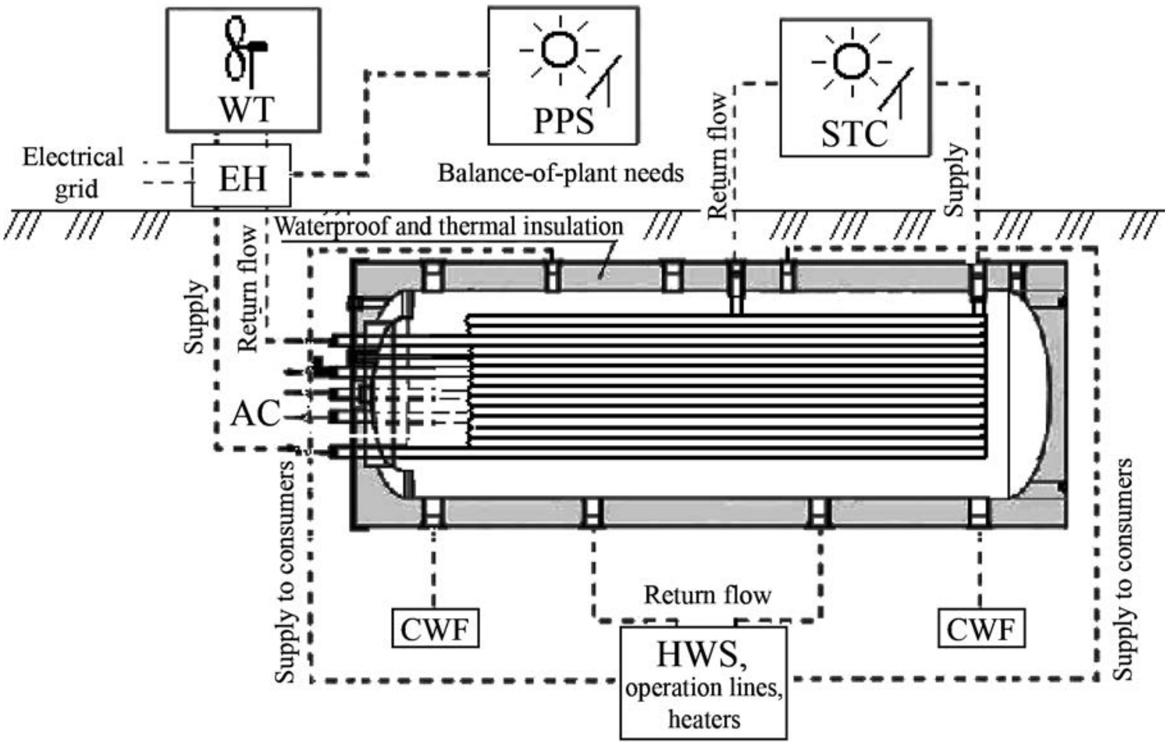

Fig. 3. The plant flow diagram for the process of generation and accumulation of the renewable energy inside mine cavities:

WT – wind turbine; PPS – photovoltaic power station; STC – solar thermal collector; EH – electric heater; CWF – cold water facilities; HWS – hot-water supply; AC – air circuit covered with the thermal insulation layer and with the waterproof membrane. The reinforced concrete structures should assure the stability of the walls and roof of the cavity.

Depending on the hot water consumption for a definite period of time, we can determine the required volume of the heat accumulator, given the liquid heat capacity, which, for example for water, equals 4.2 kJ/(kg · °C).

The thermal energy that can be accumulated in the heat carrying fluid located inside the mine cavity can be determined by the following formula

$$Q = m \cdot c \cdot (t_2 - t_1), \tag{1}$$

where m is the mass of the matter, kg; c is the specific thermal capacity of the accumulating matter, kJ/(kg · °C); $t_2 - t_1$ is the difference between the initial and final temperature of the matter, °C.

Over the year the dynamics of consumption of the energy for the purposes of space heating and the productivity of the solar thermal collector are asynchronous. They differ in quantity by the loss rate, which depends on various factors (Fig. 4).

Fig. 5 demonstrates the temperature dynamics for the coldest month of the year during the heating season, by the data of Odessa Hydrometeorological Centre.

January appeared the coldest month during the heating season; the heat consumption is shown in Fig. 6.

Water and water-salt solutions, natural stone and pebble stone, and air are usually used as a heat-retaining matter.

The duration of storage of the accumulated thermal energy depends on the design of the reservoir, thermal capacity and mass of the heat-retaining matter, the productivity of the thermal energy source. It can be calculated by the formula

$$\tau = \frac{Q}{Q_{source}\eta_{\text{source}}\eta_{\text{accum}}\eta_{\text{piping}}}, \tag{2}$$

where Q_{source} is the productivity of the thermal energy source, J per year; η_{source}, η_{accum}, η_{piping}, are the efficiency factors of the energy source, accumulator, and heat transport system respectively.

The area of solar collector is approximately determined by the specific generation on a sunny day. For the storage period, the heat will be lost through the walls of the container and during its transportation of the heat carrier from the source to consumers. The loss is taken into account during the calculation.

This process of the renewable energy accumulation/generation will last over the year depending on the need in the energy. Simultaneously with the accumulation of thermal energy, the heat extraction will take place through the pipeline (by heat transfer fluid or air) to the consumers of thermal energy, for the purposes of heating, hot water, and hot air for technological processes of enterprises, for everyday needs of the city, etc.

The second option implies using the wind turbine as the source of renewable energy. Its capacity can be determined by the formula [2]

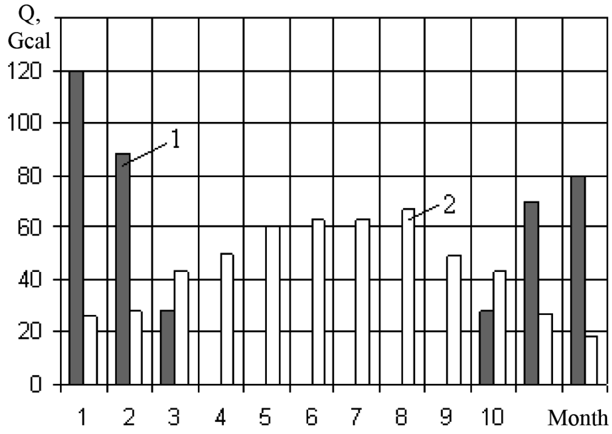

Fig. 4. The dynamics of thermal energy over the course of the year in the Odessa region:

1 – customers' consumption; 2 – productivity of the solar thermal collector

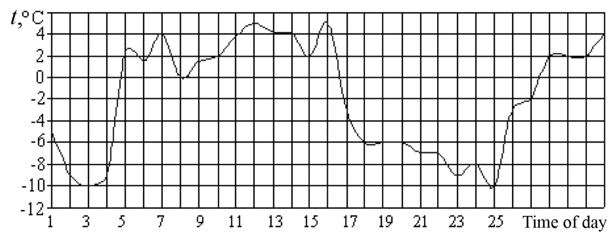

Fig. 5. The dynamics of the ambient temperature in the Odessa region in January 2016

Fig. 6. The dynamics of heat consumption for space heating depending on the ambient temperature

$$P = 0.5\rho S V^3, \tag{3}$$

where ρ is the air density, which approximately is equal to 1.23 kg/m^3; S is the swept area, m^2; V^3 is the wind velocity, which varies depending on the season, the region of location and height of the tower, m/s.

Hellmann's empirical expression allows calculating of the wind velocity at the given height of the wind turbine axis

$$\frac{V}{V_o} = \left(\frac{h}{h_o}\right)^b, \tag{4}$$

where V_o is the value of the wind velocity at the given height h_o, m; h is real height of the axis of the wind turbine installed on the tower, m; V is the target value of the wind velocity, m/s; b is the parameter that takes into account the relief of the location area, which is taken from the Table.

The average wind velocity in the Odessa region varies over the year and it will determine the wind turbine performance dynamics (Fig. 7).

The diagram of the photovoltaic power station productivity generally follows the shape of that for the solar thermal collector (Fig. 4).

The third option implies combined heating of the heat carrier by the wind and photovoltaic power stations, which power an electric heating unit. The thermal energy is delivered to the accumulator through a heating conduit.

When the load on the electric greed is minimal (at night), if needed, the heat carrier can be heated by means of the city's electric network with the purpose of leveling the daily load pattern, which allows reducing the fuel consumption at thermal power stations. The fuel consumption can be calculated by the formula [3]

$$\Delta G = \frac{P_{\min} T_{\max} q_o}{\alpha}, \qquad (5)$$

Table

Wind shear

b	Location Area Description
0.10	Perfectly smooth surface (undisturbed water)
0.20	Flat pasture, low shrubs
0.24	Trees, hills, buildings in the area
0.28	Not far from trees or buildings
0.30	Close to trees or buildings
0.40	Surrounded by high trees or buildings

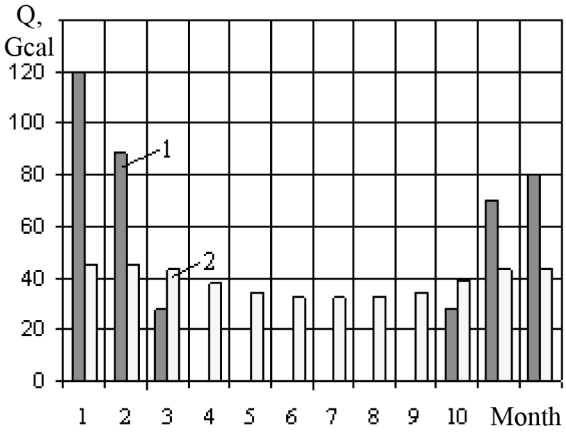

Fig. 7. The dynamics of the thermal energy over the year in the Odessa region:

1 — customers' consumption; 2 — wind turbine productivity

where ΔG is the fuel consumption at thermal power station; $P_{\min}$ is minimum electrical load per calendar day, kW; $T_{\max}$ is the annual number of clocks of use of a maximum load; q_0 is the fuel use per kW · hr; is load curve irregularity factor ($P_{\min}/P_{\max}$).

The decrease of harmful emissions into the environment caused by the reducing of fuel combustion at thermal power plants and the reducing of network losses through leveling the daily load pattern can be determined by the formula [3]

$$E_{ji} = \Delta W c_{ji}, \qquad (6)$$

where ΔW is the amount of saved power, kW · hr; c_{ji} is the emission index of the jth harmful substance of the ith type of fuel, g/kW · hr.

The facilities for the wind and photovoltaic power stations should be chosen considering their capacity and customers' consumption. The combination of the two sources of renewable energy allows regulating the economical heat generation for consumers (Fig. 8).

The surplus electric energy caused by the reduction of heat consumption in the warmer months of the heating season can be directed into the power grid of the city.

The fourth option is to use the wind turbine and solar thermal collector, for which the dynamics of generation and consumption of energy is equal to the one shown in Fig. 6.

The net present value of the introduction of the investment project of the heat collector utilization can be determined as follows

$$NPV = \sum_{t=0}^{25} \frac{R_t - B_t}{(1+\mathrm{k})}, \qquad (7)$$

where R_t is the income for the tth year; B_t is the annual expenditure for the tth year, which is determined as the difference between capital costs per annum K_t and exploitation costs $C_{ex.t}$; k is the discount factor at bank credit interest rate.

If the net present value for the period of its exploitation is positive, the investment project is considered

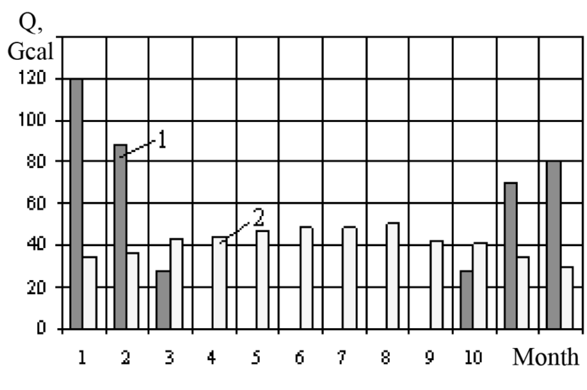

Fig. 8. The dynamics of thermal energy around the year in the Odessa region:

1 — customers' consumption; 2 — wind turbine, photovoltaic power station, and solar thermal collector worth implementation; if the value is negative, it is considered unprofitable.

The payback period for a source of renewable energy is determined through the successive calculation of the net profit for each subsequent year for the whole period of realization of investments.

The approximate dynamics of the net present value of the projects involving different sources of energy was predicted for the period of 15 years, since the future changes in the price of the equipment, common and «green» tariffs for thermal energy, cost of materials, mounting works, exploitation costs and other factors are unpredictable.

The results of calculation of the net present value of the projects are presented in the Fig. 9.

According to preliminary calculations, the net present value (discounted) for the period of 15 years for the project with solar thermal collector makes UAH 2.056 million; for the project with photovoltaic power station it makes UAH 1.380 million; for the project with wind power station it makes UAH 470 thousand. However, the service life of this facilities is 20–25 years, thus the value will increase during the subsequent 5–10 years.

The estimation shows that the internal rate of return (IRR) will amount 20, 28, and 39 % for the wind turbine, photovoltaic power station, and solar thermal collector respectively.

In addition, for the exploitation period, this way of energy accumulation will save nearly 4.2 thousand tons of reference fuel, which in its turn will prevent the emission of 11.4 thousand tons of greenhouse gasses.

Conclusion. The proposed options for the use of renewable energy sources such as solar collectors, wind and solar power plants and technologies of the energy storage in mine cavities (catacombs) is the basis for the development of specific (depending on the climatic conditions of a region) investment projects on providing industrial enterprises or housing utilities with renewable energy.

The availability of mines (catacombs) almost under the entire territory of the city of Odessa allows building such accumulative reservoirs and install renewable energy sources close to the energy consumers that will minimize losses in the distribution network.

The further study requires an in-depth analysis of the energy and temperature balance to determine the duration of the accumulated heat storage and the amount of energy that can be used for various needs of the city, given the renewable energy production schedule and daily pattern of its use.

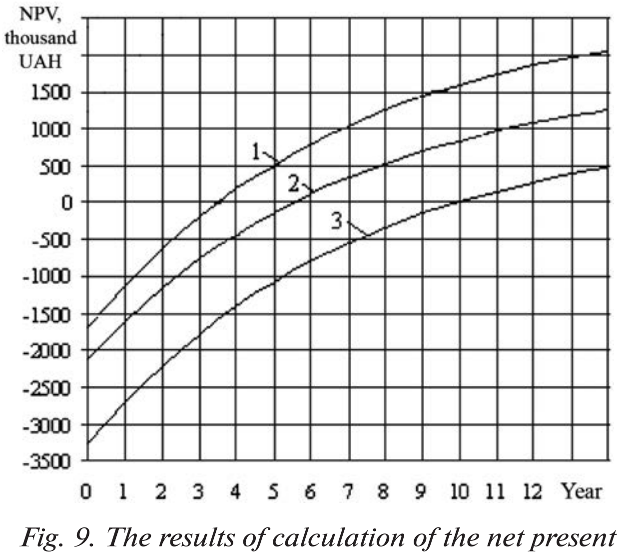

Fig. 9. The results of calculation of the net present value dynamics of a project with:

1 – solar thermal collector; 2 – photovoltaic power station; 3 – wind power station

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Мета. Розроблення технології та представлення результатів розрахунку ефективності використання відпрацьованих шахтних порожнин в якості акумулятора відновлюваної енергії.

Методика. Математичне моделювання технології отримання, акумулювання, використання сонячної, вітрової, геотермальної енергії, що акумулюється в шахтних порожнинах (Одеських катакомбах).

Результати. Показана висока ефективність й інвестиційна привабливість використання відпрацьованих шахтних порожнин в якості акумулятора відновлюваної енергії та використання її для технологічних потреб у виробничих процесах, гарячого водопостачання, опалення в зимовий період та охолодження приміщень у літній час за рахунок геотермальної енергії кам'янистих стін.

Наукова новизна. Полягає в застосуванні інноваційної технології використання унікальних відпрацьованих Одеських шахт (катакомб) в якості акумулятора відновлюваної енергії для потреб міста.

Практична значимість. Проведено аналіз варіантів використання різних типів джерел відновлюваної енергії в Одеському регіоні, визначена їх енергетична, економічна, екологічна ефективність та орієнтовні строки окупності такого проекту з урахуванням ринкових умов, що даватиме практично необмежену економію традиційних енергоресурсів за мінімального негативного впливу на навколишнє середовище.

Ключові слова: *шахта, акумулювання, геліосистема, вітрогенератор, сонячна електростанція, поновлювана енергія, довкілля*

Цель. Разработка технологии и представление результатов расчета эффективности использования отработанных шахтных пустот в качестве аккумулятора возобновляемой энергии.

Методика. Математическое моделирование технологии получения, сбережения, использования солнечной, ветровой, геотермальной энергии, которая аккумулируется в отработанных шахтных пустотах (Одесских катакомбах).

Результаты. Показана высокая эффективность и инвестиционная привлекательность использования отработанных шахтных пустот в качестве аккумулятора возобновляемой энергии для технологических потребностей в производственных процессах, системах горячего водоснабжения, отопления в зимний период и охлаждения помещений в летний период за счет геотермальной энергии каменистых стен.

Научная новизна. Состоит в инновационной технологии использования уникальных отработанных Одесских шахт (катакомб) в качестве аккумулятора возобновляемой энергии для нужд города.

Практическая значимость. Проведен анализ предложенных вариантов использования разных типов источников возобновляемой энергии в Одесском регионе, определена их энергетическая, экономическая, экологическая эффективность и ориентировочные сроки окупаемости такого проекта с учетом рыночных условий, что даст практически неограниченную экономию традиционных энергоресурсов при минимальном негативном влиянии на окружающую среду.

Ключевые слова: *шахта, аккумулирование, гелиосистема, ветрогенератор, солнечная электростанция, возобновляемая энергия, окружающая среда*

Рекомендовано до публікації докт. техн. наук В. С. Петрушиним. Дата надходження рукопису 14.10.15.